AN EVALUATION OF THE PRACTICAL USE OF SOIL MOISTURE SENSORS FOR IRRIGATION SCHEDULING

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An evaluation of the practical use of soil moisture sensors for irrigation scheduling

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Five soil moisture sensors have been evaluated for their use as practical irrigation scheduling tools. The sensors are: the neutron probe; the Time Domain Reflectometry (TDR) probe; tensiometers; 'Watermark' electrical resistance sensors; and gypsum blocks.

The sensors were evaluated both by literature review and in a ten-month field trial. All the sensor types were installed in the trial plot in depthwise arrays, with threefold replication of each array. the plot was subjected to a single wetting-drying cycle by use of a mobile rainshelter and irrigation.

Measurements of the electrical resistance of the Watermark sensors and gypsum blocks and of soil temperatures, were automatically recorded using a datalogger with a multiplexer. The resistance sensors were also read manually using hand-held meters supplied by the sensor manufacturers. Resistances were corrected for temperature, and in the case of the Watermarks converted to soil water suctions using the calibration built into the manufacturer's hand-held meter.

After the sensor measurements were completed the site was excavated to: (i) assess the effect of soil spatial variability on sensor measurements (using bulk density and soil moisture content as indicators of variability; and (ii) assess the sensor-to-soil contact.

Thin irregular, and often discontinuous bands of finer textured material were found in the BC horizon, below approximately 50 cm. Soil water movement is believed to have been strongly influenced in this horizon because of the geometry of these bands and their relatively poorer permeability. This had contributed to measurement variability.

The TDR probe is recommended as an alternative scheduling tool to the neutron probe for most irrigation scheduling requirements, and the limitations of both methods are described. Due to high sensor cost (c. NZ$12 to 13000), it is expected that their use in New Zealand will be restricted to scheduling consultants.

The two electrical resistance sensors (Watermark and gypsum block, both measuring water potential) are also strongly recommended for certain scheduling applications in New Zealand. It was found that more precise measurements of suction were achieved by adjusting resistance for soil temperature. It is recommended that gypsum block meters should have a temperature compensation circuit for their readings.

The electrical resistance sensors suffered from hysteresis. This was most apparent after the sensors had been registering relatively high suctions, and when the soil surrounding the sensors was then only partially re-wetted. These sensors are therefore best used for scheduling when the soil is completely re-wetted.

Averaged suction readings from replicated 'Watermark' sensors compared favourably with averaged tensiometer readings, at 30 cm depth. Inter-sensor variation among the Watermarks was greater than among the tensiometers. Several advantages of the Watermark sensor make it a practical alternative to the tensiometer, i.e. greater suction range (the Watermark range is c.10 to 150 kPa and the tensiometer range is c. 0 to 85 kPa), low maintenance, and cost. In contrast, gypsum blocks are most appropriate for 'dryland' cropping. Also, they could be used as supplementary diagnostic tools at the bottom of the root zone to monitor potential undersirable drainage losses due to over-irrigation.

Practical recommendations are also made for the use of these sensors for scheduling. These recommendations include the appropriate use of each sensor type, the selection of a suitable measurement site(s), the number of sensors (or measurements) required, and depth considerations.

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TABLE OF CONTENTS

LIST OF FIGURES vi

LIST OF TABLES vii

LIST OF PLATES viii

SELECTED SYMBOLS AND ABBREVIATIONS ix

CHAPTER 1 INTRODUCTION 1

1.1 The research objectives. 2

1.2 Thesis structure. 3

CHAPTER 2 LITERATURE REVIEW 4

2.1 The benefits of irrigation scheduling. 4

2.2 Objectives of irrigation scheduling. 6

2.3 Principles of irrigation scheduling. 6

2.3.1 Soil-based methods. 7

2.3.2 Plant-based methods. 7

2.3.3 Soil water balance (or budget) methods. 9

2.3.4 Using the soil water balance to time irrigations. 11

2.3.5 Errors using soil water balance 12

2.4 Concepts of plant-available water. 12

2.5 Irrigation scheduling services. 13

2.6 Comparison of irrigation scheduling methods. 13

CHAPTER 3 REVIEW OF SOIL MOISTURE SENSORS UNDER EVALUATION. 16

3.1 Neutron probe 16

3.1.1 History. 16

3.1.2 Theory of operation. 16

3.1.6 The use of count standards. 18
3.1.7 Access tubes. 19
3.1.8 Installation procedures. 19
3.1.9 Calibration methods. 20
3.1.10 Factors affecting neutron probe calibration. 21
3.1.11 Measurement bias and precision. 21
3.1.12 Irrigation scheduling using the neutron probe. 23
3.2. Time Domain Reflectometry. 23
3.2.1 Principle of TDR. 23
3.2.2 Instrument design. 24
3.2.3 Transmission lines (wave-guides). 24
3.2.4 Wave-guide installation procedures. 25
3.2.5 Sample volume. 26
3.2.6 Measurement precision. 27
3.2.7 Effect of soil layering. 27
3.2.8 Salinity. 27
3.2.9 Automation. 28
3.3 Tensiometers. 28
3.3.1 Tensiometer operation. 28
3.3.2 Instrument design. 28
3.3.3 The principle of tensiometry. 29
3.3.4 Design Limitations. 29
3.3.5 Tensiometer response times. 30
3.3.6 Measurement accuracy. 31
3.3.7 Portable Tensiometers. 31
3.3.8 Installation procedures. 32
3.3.9 Automatic irrigation systems. 32
3.3.10 Irrigation scheduling using tensiometers. 32
3.4 Electrical resistance sensors. 33
3.4.1 Measurement of sensor resistance. 34
3.4.2 Sensor hysteresis. 35
3.4.3 Temperature effects. 35
3.4.4 Gypsum dissolution. 36
3.4.5 Measurement range. 36
3.4.6 Sensor response times. 36
3.4.7 Sensor Calibration. 37
3.4.8 Sensor measurement errors. 37

3.4.9 Installation requirements. 38
3.4.10 Field use of electrical resistance sensors. 38

CHAPTER 4 METHODS AND MATERIALS. 39
4.1 Introduction. 39
4.2 Field evaluation of the sensors. 42
4.2.1 The field site. 43
4.3 Sensor installation. 46
4.3.1 The neutron probe. 46
4.3.2 TDR wave-guides. 46
4.3.3 Tensiometers. 48
4.3.4 Electrical resistance sensors. 48
4.3.5 Thermistors. 48
4.4 Neutron probe calibration. 49
4.5 Measurement intervals. 49
4.6 Logging the electrical resistance and thermistor sensors. 49
4.7 Sensor excavation (*post mortem*). 52

CHAPTER 5. RESULTS AND DISCUSSION 53
5.1 Trial plot excavation. 53
5.1.1 Textural variation. 53
5.1.2 Bulk density measurements. 56
5.1.3 Soil moisture measurements. 57
5.1.4 Sensor-soil contact. 57
5.1.5 Roots. 57
5.2 Irrigation and rainfall events. 59
5.2.1 Rainshelter effectiveness. 59
5.2.2 Lateral flow effects. 59
5.3 Sensor results from the field trial. 62
5.3.1 Neutron probe. 62
5.3.2 TDR Probe. 63
The use of weighted averages. 65
5.3.3 Comparison of the neutron probe and TDR results. 67
Comparison of instrument calibrations. 67
5.3.4 Tensiometers. 69
5.3.4.1 Tensiometer measurement range. 72
5.3.4.2 Maintenance requirements. 72

5.3.5 Data-logged results: sensor resistance and soil temperature. 73
5.3.6 Watermark sensors 74
5.3.6.1 Temperature "corrections". 74
5.3.6.2. Watermark suction measurements. 77
5.3.6.3. Comparison of Watermark and tensiometer suction measurements. 77
5.3.6.4. Sensors at 30cm depth. 81
5.3.6.5. Sensors at 60cm depth. 81
5.3.7 Gypsum blocks. 85
5.3.7.1 Temperature correction. 85
5.3.7.2 The relationship between resistance and meter readings. . . 86
5.3.7.3 Gypsum block resistance readings. 88
5.3.8 Electrical resistance sensors: response and hysteresis. 89
5.4. Summary of sensor characteristics. 89

CHAPTER 6 SELECTING SOIL MOISTURE SENSORS FOR IRRIGATION SCHEDULING. 95
6.1 Introduction. 95
6.2 Considerations for sensor selection. 95
6.2.1 Crop factors. 95
6.2.2 Soil factors. 97
6.2.3 Irrigation methods. 99
6.2.4 Costs. 102
6.2.5 Personal preference. 103
6.3 Summary of the suitability of the investigated sensors for irrigation scheduling. 105
6.4 Recommendations for practical use of the sensors for scheduling. 109
6.4.1 Number of sensor stations. 109
6.4.2. Sensor numbers and measurement depths. 110
6.4.3. Measurement interval. 111

CHAPTER 7 SUMMARY AND CONCLUSIONS 113
7.1 Summary. 113
7.2 Conclusions. 115
7.3 Future research. 116

REFERENCES. 117

APPENDICES. 129
Appendix 1 CR10 datalogger program for the electrical resistance sensors in the field. The program was written using the 'Edlog'software, part of the PC208 package (Campbell Scientific, Inc.). 129
1.1 Program 1: Sensor measurement and output every four hours. 129
1.2 Program 2: Measurement and output every 24 hours. 130

Appendix 2 Soil moisture sensor field evaluation data (on floppy disk). 133
2.1 Neutron probe data 133
2.2 TDR data 133
2.3 Tensiometer data 133
2.4. Watermark logged resistance and temperature data 133
2.5. Gypsum block logged resistance and temperature data 133

LIST OF FIGURES

Figure 3.1: Diagram of the neutron probe in use (from Bell, 1987). 17

Figure 3.2: A schematic diagram of a TDR probe and its display unit (from Topp and Davis, 1985). 25

Figure 3.3: Diagram of a bourdon gauge-type tensiometer. 29

Figure 3.4: Cutaway diagrams of a) a concentric cylindrical electrode gypsum block, and b) a parallel rectangular electrode gypsum block (from Wellings *et al.*, 1986). 33

Figure 3.5: Cutaway diagram of a Watermark resistance sensor (from McCann *et al.*, 1992). 34

Figure 4.1: Plan of sensor installations in the field plot. 44

Figure 4.2: Wiring of the electrical resistance sensors to the CR10 datalogger and AM32 multiplexer. 50

Figure 4.3: Wiring of the thermistors to the CR10 datalogger. 51

Figure 5.1: Soil textural profiles for three sensor 'clusters' (tensiometers, Watermark sensors and gypsum blocks) within the field plot 54

Figure 5.2: Lateral flow effects for tube 3 shown by successive neutron probe measurements. 61

Figure 5.3: Neutron probe measured water content for the 0 to 50cm depth for the trial period. 62

Figure 5.4: Drying sequence for the three tubes for four selected dates when θ_v between 0 and 50cm depth is: a) at full point; b) at possible irrigation trigger point; and c) is causing severe observable plant stress. 64

Figure 5.5: TDR measured changes of layer water contents (mm) over the trial period. Results represent the average of 3 sets of replicate rods. 65

Figure 5.6: TDR volumetric water contents for three layers. Weighted differences are used for the 30 to 50cm and 50 to 70cm layers. 66

Figure 5.7: Linear regressions between neutron probe and TDR measured θ_v. . 68

Figure 5.8: Tensiometer measurements of soil water suction at 30cm and 60cm depths. Each point represents the mean ± s.e. for three tensiometers at that depth. 70

Figure 5.9: The relationship between Watermark meter suction and temperature (as set on the temperature adjustment knob). Results were obtained with a fixed (13 kΩ) resistor across the meter leads. 75

Figure 5.10: Watermark meter suction (kPa) and temperature between 12.8°C and 21°C.(i.e. as Figure 5.9., but with only the lowest 4 point plotted). 75

Figure 5.11: The effect of temperature on the resistance-suction relationship for the Watermark: a) resistances non-temperature corrected; and b) resistances temperature corrected. 76

Figure 5.12: Watermark suction (kPa) measurements over two periods 78

Figure 5.13: Comparison of soil drying curves measured by Watermarks and tensiometers at 30cm depth. 79

Figure 5.14: Comparison of drying curves as measured by Watermarks and tensiometers at 60cm depth. 80

Figure 5.15: The relationship between log resistance (kΩ) and temperature for 3 gypsum blocks at 30cm depth between julian days 240 and 290. . 85

Figure 5.16: The relationship between temperature corrected resistance and gypsum block meter readings. 87

Figure 5.17: The near-linear relationship between temperature corrected resistance and meter readings, when the latter are confined to the range 10 to 80 (see Figure 5.16). 87

Figure 5.18: Calibration graph showing relationship between soil suction and gypsum block meter readings. (Redrawn from graph supplied by block manufacturer, Electronics Unlimited, Sacramento, Calif.) . . . 88

Figure 5.19: Gypsum block resistance measurements between julian days 270 (1992) and 26 (1993). 90-91

Figure 5.20: Resistance sensor responses following incomplete soil wetting. . . . 94

Figure 6.1: Tracings of the wet front several hours after sprinkler irrigation at two application rates: (i) at 102.5 mm hr^{-1} and (ii) at 4.1 mm hr^{-1}. From Clothier and Heiler (1983). 100

LIST OF TABLES

Table 4.1: The soil moisture sensors. 39

Table 4.2: Soil textural description. 43

Table 4.3: Sensor measurement depths. 44

Table 5.1: Comparison of the bulk density (Mg m^{-3}) measurements for the three "sensor profiles". The soil is a Templeton fine sandy loam. 55

Table 5.2: Comparison of gravimetrically measured θ_v (%) for the three "sensor profiles". 55
Table 5.3: Rainfall and irrigation events. 60
Table 5.4: Regressions of neutron probe measured θ_v against TDR measured θ_v. . . 67
Table 5.5: The upper limits of suction recorded by the 6 tensiometers in the field. . 72
Table 5.6: Hand-held meter suction-temperature relationship (obtained with a fixed 13 kOhm resistor in place of a Watermark sensor). 74
Table 5.7: Comparison of means ± s.e. of suction measured by Watermarks and tensiometers at 30cm depth. 82
Table 5.8: Comparison of means ± s.e. of suction measured by Watermarks and tensiometers at 60cm depth. 83
Table 5.9: Summary of sensor characteristics 92-93
Table 6.1: Summary of the suitability of the evaluated sensors for irrigation scheduling. 106-108

LIST OF PLATES

Plate 1: Neutron probe manufactured by Troxler Laboratories 40
Plate 2: 'Trase' TDR probe manufactured by Soilmoisture Equip. Corp. 40
Plate 3: Tensiometers: a) 30cm 'Irrometer' manufactured by Irrometer Co. Inc. and b) 'Jetfill' manufactured by Soilmoisture Equipment. Corp. 41
Plate 4: 'Waterwise' gypsum block and meter manufactured by Electronics Unlimited. 41
Plate 5: 'Watermark 200' electrical resistance sensor and meter manufactured by Irrometer Co. Inc. 42
Plate 6: The field plot and rain-shelter. 45
Plate 7: Neutron probe access tube installation equipment. 47
Plate 8: TDR wave-guide installation equipment - auger, guide tube and mallet. . 47
Plate 9: CR10 datalogger and AM32 multiplexer in environmentally-sealed box. 50
Plate 10: Tensiometer at 30 and 60cm installed in profile 1 (Figure 5.1a). The darker bands of finer texture within the BC horizon are visible below c.60cm. 56
Plate 11: Poor sensor-soil contact below the tensiometer cup (T6) at 60cm depth. . 58
Plate 12: Excellent sensor-soil contact below the tensiometer cup (T3) at 30cm depth 58

SELECTED SYMBOLS AND ABBREVIATIONS

ψ_m	soil water matric potential (kPa or bars)
ψ_t	total soil water potential (kPa or bars)
s	soil water suction (kPa or bars)
θ_v	volumetric soil water content (% or mm)
Ω	ohm
AWC	available water content (% or mm)
C_m	neutron count
C_s	standard neutron count
DUL	drained upper limit (%)
E_a	irrigation application efficiency (%)
ET	evapotranspiration (mm)
ET_o	reference crop, or potential, evapotranspiration (mm)
ET_c	crop evapotranspiration (mm)
I_g	gross irrigation (mm)
I_n	net irrigation (mm)
K	dielectric constant
LL	lower limit of plant extractable soil water (%)
PESW	plant extractable soil water (% or mm)
R_c	corrected resistance (Ohms)
R_s	measured resistance (Ohms)
TDR	Time Domain Reflectometry
WUE	water use efficiency

CHAPTER 1 INTRODUCTION

Irrigation is widely practised in New Zealand. Since rainfall occurs throughout the year irrigation is supplementary, but necessary to achieve full crop production. Since rainfall is unpredictable, careful irrigation water management is perhaps even more important for several reasons: to maximize crop yield and quality, reduce water and pumping costs, and minimise leaching losses of nutrients and chemicals.

A range of irrigation methods and systems are employed throughout the country. Most of the river-fed community irrigation schemes are surface irrigated (border-strip, or border-dyke), typically on shallow soils with high infiltration rates. In Canterbury there are at least 87,000 ha using border dyke irrigation (Taylor, 1981). Overhead irrigation systems of a multitude of designs, with wide ranges of application rates and application uniformities are used by individual growers to irrigate pasture, arable, and horticultural crops, whilst micro-irrigation (including trickle and micro-sprinklers) is mainly restricted to high value horticultural crops.

There has been considerable capital outlay on these various engineering systems because of the recognition of the importance of water to the plant. Water links the plant with the soil, providing a transport medium for nutrients, maintains stomata open to aid the exchange of gases and moderates soil temperature. However, there has been a lack of recognition of the importance of careful irrigation water management, hence investment in scheduling has been low. Excess irrigation can remove nutrients from the root-zone and reduce aeration, and if there is surface runoff a part of the valuable growing medium (soil) can be removed. An unflattering, but perhaps accurate, analogy has likened irrigation practice to a dinosaur, with a huge body, i.e. the irrigation application systems, but a tiny brain, i.e. the rational control of the water by scheduling (Buchan and Thomas, 1992).

A typical experience of neutron probe scheduling consultants in Canterbury has been that growers using their service had previously tended to irrigate too infrequently (i.e. after the onset of crop stress and potential yield had been reduced), and then to over-irrigate, so that water and leached nutrients were lost below the root-zone.

Scotter and Clothier (1986) suspected that there are often large drainage and nutrient leaching losses resulting from irrigation, largely as a result of poor understanding of the relationship between the irrigation method and the movement and storage of irrigation water in the soil. This is supported by recorded higher rates of nitrate leaching below irrigated land than below non-irrigated land (Burden, 1982), which is in common with many other parts of the world that are realising the problems of poor irrigation water management.

Some of the benefits of using scheduling appear to be slowly diffusing between irrigation practitioners, evident by an increasing demand for neutron probe scheduling services in New Zealand. For example, one commercial scheduler, with the largest client base in the South Island does not need to advertise his service. The neutron probe is a proven, reliable and practical scheduling tool, and is used in many areas overseas. In Australia more than 500 probes are now in use, most in the hands of individual growers. Considering that the cost of a neutron probe is approximately NZ$12,000, the benefits to these growers must be considerable.

However, other soil moisture technologies are also available, e.g. tensiometers and electrical resistance sensors, and some more recently developed probes, e.g. Time Domain Reflectometry (TDR) probes, and capacitance probes. Each will have its own benefits and limitations. Likewise this is the case for irrigation scheduling methods in general.

1.1 The research objectives.

The objectives of the research project described in this thesis were to:

(1) Evaluate the practical benefits and limitations of five commercially available soil moisture sensors for irrigation scheduling.

(2) Attempt to promote these techniques in practice, by suggesting practical methods for using these sensors for irrigation scheduling, and by publishing results across the literature 'spectrum', from popular publications to formal journals.

1.2 Thesis structure.

Firstly a review is given in Chapters 2 and 3 of the methods and principles of scheduling irrigation, including comparative studies of scheduling methods, and the characteristics of the soil moisture sensors that are being investigated. A description of the field study follows in Chapter 4. The field results are then analyzed and discussed in Chapter 5, including a summary of the characteristics of the sensors. In Chapter 6 the suitability of the sensors for a range of irrigation, cropping and soil types is discussed and recommendations made regarding the use of the sensors. Practical suggestions are made concerning the number of sensors, sites and depths to be used for scheduling.

CHAPTER 2 LITERATURE REVIEW

Irrigation scheduling is based on two fundamental decisions: when to irrigate and how much water to apply. Jensen (1981) provides an excellent description of the nature of irrigation scheduling as a planning and decision-making activity that the irrigator is involved in before and during most of the growing season for each crop that is grown.

Scientific approaches are required. Hanks and Nimah (1988) list some of the factors that govern irrigation scheduling as: the crop; its stage of growth; the extent of root development; climatic conditions; the soil water holding capacity; the ability of the soil to transmit water; the amount of water held at the beginning of crop growth; as well as soil salinity and fertility.

2.1 The benefits of irrigation scheduling.

(a) Crop yield.

Various crop water use studies in New Zealand have shown the benefits of irrigation for crop production, for example, for potatoes (Martin *et al.*, 1992), field beans (Newton and Hill, 1987), pasture (McAneney and Judd, 1983), barley (Carter and Stoker, 1985). The benefits of these types of studies in terms of scheduling and water allocation in New Zealand have been discussed by Wilson (1985).

A recent review by Howell (1990) describes the relationships between irrigation, yield and evapotranspiration (ET). One simple model that has been used to help in irrigation planning and design is described by Doorenbos and Kassam (1979), estimating economic crop yield as a function of ET (Eq. 2.1):

$$\frac{Y_a}{Y_m} = 1 - k_y \left(1 - \frac{ET_a}{ET_m}\right) \qquad 2.1$$

where, Ya is actual crop yield, Ym is the maximum potential yield, ky is an empirically derived crop yield response factor, ETa is the actual ET, and ETm the maximum ET.

Their assumptions for applying ky values are: that the response between relative yield (Ya/Ym) and relative ET (ETa/ETm) is linear; and that the above equation 2.1 is valid

for soil water deficits to about 50 % of the plant-available water. ky values are crop specific and may vary between stages of growth, i.e. because of different stages of crop sensitivity to stress. Experimentally derived ky values have been published in tabulated form for a number of crops (Doorenbos and Kassam, 1979).

Wilson (1985) describes a model that has been used to define yield responses to water deficit in a number of New Zealand studies. The model can be expressed as two equations (Eqs. 2.2 and 2.3).

$$Y_a = Y_m \quad (D_m \leq D_l) \qquad 2.2$$

and,

$$Y_a = Y_m[1 - c\,(D_m - D_l)], \quad (D_m > D_l) \qquad 2.3$$

where, D_m (in mm) is the maximum potential soil water deficit, D_l (in mm) is a critical soil moisture deficit above which crop growth is retarded, and c is the fractional loss of potential yield for each mm of D_m beyond D_l.

Water use efficiency (WUE) data, defined as the unit of economic crop yield per unit of water used by the crop, can be valuable for estimating economic returns from irrigation. For example, Martin *et al.* (1992) estimated approximate economic returns for potatoes, per 50 mm of irrigation water, of NZ\$500 ha^{-1} before and \$1200 ha^{-1} during the main phase of tuber bulking,and compared these with the variable costs of sprinkler irrigation of up to \$21 ha^{-1} 50 mm^{-1}.

(b) Crop quality.

Crop quality improvements have also been noted. An increase of the mean size of kiwifruit resulted from irrigation, whilst removal of irrigation slowed down crop growth and reduced the overall mean fruit size (Judd *et al.*, 1989).

(c) Water and power savings.

Other economic benefits may result. In a study on economic costs of centre-pivot systems in Nebraska, USA, it was found that energy savings of 17%, water savings of 11%, and a 3.5% increase in yield resulted from careful irrigation scheduling using tensiometers (Kranz *et al.*, 1992). In another study in California, water savings of between 20 and 40% were made using scheduling by gypsum blocks, compared with no scheduling (Richardson *et al.*, 1989).

(d) Environmental protection.

A further benefit of irrigation scheduling is the reduction of leaching of nutrients and possibly pesticides from the rootzone from over-irrigation, which may result in 'downstream' contamination of water resources (see Chapter 1). Clothier (1989) commenting on world-wide irrigation practices suggests that it is the lack of knowledge of the requisite amount of water to apply which has resulted in the raising of water tables and increasing nitrification of groundwater.

2.2 Objectives of irrigation scheduling.

Martin *et al.* (1990) list six possible objectives for irrigation scheduling:

- (i) for maximum economic return;
- (ii) to minimise irrigation costs;
- (iii) for maximum yield;
- (iv) for optimal use of limited irrigation water;
- (v) to minimise ground water pollution; and,
- (vi) to optimise production from a limited irrigation system capacity

Soil and water salinity management is another possible objective (Hill, 1991). Whilst salt problems occur in many irrigated areas in the world, they are unlikely to be a problem in irrigated crops in New Zealand.

2.3 Principles of irrigation scheduling.

Irrigation scheduling is based on (a) the monitoring of soil water changes and/or plant responses and (b) the computation of a soil water balance. An excellent review has been written by Martin *et al.* (1990).

2.3.1 Soil-based methods.

Irrigation scheduling by soil moisture measurement is probably the oldest, and most popular, of the scheduling methods (Campbell and Campbell, 1982). Soil-based irrigation scheduling methods utilise either a measure of volumetric soil water content (θ_v) or soil matric potential (ψ_m). Both θ_v and ψ_m are functionally related to each other; the graphic representation of this is the soil water characteristic curve (Hillel, 1982).

Matric potential has been defined as the negative pressure or suction experienced by water as a result of its affinity for the soil matrix (Mullins, 1991). For the convenience of dropping the negative sign matric suction, or suction, (*s*) is often preferred. Also, commercially available tensiometers read suction. For these reasons the concept of positive soil water suction is used in preference to negative matric potential, throughout this thesis. Volumetric soil water content is the volume of water per volume of dry soil.

There are a number of comprehensive reviews describing a range of methods for measuring suction *s* (e.g. Mullins, 1991; Campbell, 1988; Campbell and Gee, 1986; and Cassell and Klute, 1986) and soil water content θ_v (Gardner *et al.*, 1991; Gardner, 1986). These are primarily aimed at the researcher. Relatively little has been written on the relative merits of soil water measuring methods, to help the grower decide the best methods to adopt, with notable exceptions of Campbell and Mulla (1990); Campbell and Campbell (1982); and Phene *et al.* (1990a,b).

A review of some of the main soil sensors, specifically the five under evaluation for irrigation scheduling, is given in Chapter 3.

2.3.2 Plant-based methods.

Since the main objective of irrigation is to provide water to the plant, then a measure of plant water status should be appropriate for scheduling. According to Reginato and Howe (1985) there is no substitute for interrogating the plant itself when deciding when to irrigate. However, plant water status is extremely dynamic, mainly because of the effect of atmospheric evaporative demand. As a result, it is not a simple indicator of the reserves of plant extractable water in the soil, or timing of irrigations. Practical methods of measuring plant water status for irrigation have been reviewed by Hsiao (1990), and Phene *et al.* (1990a,b). Briefly, the main methods in use are as follows:

a) The pressure chamber.
This method (also known as the 'pressure bomb') is widely used mainly for scheduling irrigations for cotton (Hsiao, 1990). Since cotton undergoes strong osmotic adjustment under water stress this allows leaf water potential to drop substantially without a large reduction in photosynthesis, whilst restricting unwanted vegetative growth. Leaf water measurements have tended to be taken predawn or dawn, when daily potentials are normally lowest. However, it is suggested that this may not be a sufficiently sensitive indicator of plant water status to serve as a guide for irrigation scheduling (Hsiao, 1990).

b) Stomatal opening.
Water stress will affect stomatal closure. As plant water potential decreases stomata close reducing transpiration. Measurement of stomatal conductance is made using a porometer. The main drawback of this method is that it is generally not sensitive enough. By the time stress is apparent expansive growth is inhibited.

c) Leaf and stem elongation.
This is the most sensitive indicator for the onset of water stress. Unfortunately factors other than water stress may be responsible for reduction in expansive growth. Problems may arise due to changes in growth stage when leaf and stem elongation is less sensitive to changes in plant water status, making useful measurements impossible.

d) Infrared thermometry (IRT).
The measurement of canopy temperature using this method is simple and quick, and readily automated. The use of an empirically derived crop water stress index (CWSI) is most popular, although a number of indices have been developed (Jackson, 1982).

There are still some problems with its use in scheduling. It is only sensitive when the plant is becoming stressed. Stegman and Soderland (1992) found that because of this there was inadequate lead time to schedule irrigations, unless a water balance method was used in conjunction with the IRT. However, Reginato and Howe (1985) did not report such a problem when scheduling irrigation for cotton.

The use of the IRT for scheduling peas and beans has been investigated in Canterbury (Scott, 1990). It was concluded that the difference between canopy temperature of stressed and unstressed crops held promise, but further investigation of the effect of crop and weather variables was required.

In summary, the reliability of using plant indicators as scheduling tools must therefore be carefully considered. It has been suggested that these measurements are best used to complement soil and weather methods. However, because they integrate the current performance and health of the plant, and soil water conditions they can give valuable information.

2.3.3 Soil water balance (or budget) methods.

All these methods are based on the soil water balance of the so-called root zone which may be written as:

$$D_e = D_b - I_n - P_e - U + ET_c + D_p \qquad 2.4$$

where, D_b and D_e (mm) are soil water deficits at the beginning and end of the period, I_n is net irrigation, P_e is effective rainfall, U is upward flow from below the root zone, ET_c is the estimated crop water use, and D_p is deep percolation loss.

There are a range of methods described in the literature ranging from very sophisticated computer programs (Hill, 1991; Harrington and Heerman, 1981; Shlomo and Israeli, 1989) to very basic budget sheets designed for on-farm use (Jamieson *et al.*, no date).

Determination of the maximum allowable soil moisture deficit between irrigations requires the estimation of the root zone water storage capacity. This requires estimates of (i) the volume of the plant extractable soil water and (ii) the maximum effective rooting depth. The concepts of plant-available water are discussed below in section 2.4.

(a) Rooting depths (R_d).
Generally the effective rooting depth is assumed to be less than the maximum rooting depth of a mature plant because of decreased root density in the lower part of the root zone. Guides for estimating maximum effective rooting depths have been published (Jensen *et al.*, 1990; Martin *et al.*, 1990; Doorenbos and Pruitt, 1977). A number of

calculations for approximating root growth between planting (or emergence) and the time of maximum effective rooting depth (soon after complete crop canopy is attained) have also been described (Martin *et al.*, 1990).

(b) Management allowed depletion (MAD).

This is defined as the calculated fraction of the plant extractable water that can be can be depleted between irrigations without causing yield reduction. Approximate allowable depletion levels for a number of crops have been suggested (Doorenbos and Pruitt,1977; Doorenbos and Kassam, 1979). Typical values are:

0.25 to 0.4	High-value, shallow or sparsely rooted crops.
0.5	Deep-rooted crops.
0.6 to 0.65	Low value, deep-rooted crops (Jensen *et al.*, 1990).

The allowable depletion (mm) is calculated by:

$$A_d = p.R_d.S_e \qquad 2.5$$

where, A_d (mm) is the allowable depletion, R_d is the effective rooting depth (m), p is the management allowed depletion , and S_e is the plant extractable water (mm m^{-1}).

(c) Evapotranspiration.

Various methods for the calculation of ET_o (reference crop or potential evapotranspiration) have been comprehensively described by Jensen *et al.*, (1990). Doorenbos and Pruitt (1977) describe the calculation of crop evapotranspiration ET_c from ET_o using crop coefficients (kc) from four different climate methods (modified Penman, Blaney-Criddle, radiation, and pan evaporation). Computer-based methods normally use algorithms to compute kc values for a range of crops (e.g. Hill, 1991)

In New Zealand the Priestley-Taylor radiation-based method of calculating ET_o has been recommended (Clothier *et al.*, 1982). Morgan (1991) comparing lysimeter and Priestley-Taylor measurements of ET_o, in Canterbury, recommended using a summer correction factor for irrigation scheduling because of strong advective conditions over the summer in this region.

(d) Net irrigation (I_n).

This is calculated by

$$I_n = I_g.E_a \qquad 2.6$$

where, I_g is the gross irrigation depth (mm) and E_a is the field application efficiency. Approximate values for E_a for irrigation systems have been suggested by Doorenbos and Pruitt (1977) and Martin *et al.* (1990).

(e) Effective rainfall (P_e).

This is defined as the rainfall that reaches the root zone. Some rainfall may be lost to interception evaporation and runoff

(f) Upward flow (U).

This can be an important factor when the water table is close to the bottom of the root zone (typically at approximately 1 m depth), and is influenced by the soil texture. Upward movement is influenced by a) capillarity, and b) hydraulic conductivity of the soil. The highest rates of upward flow are found in medium textured soils, due to the combination of these effects.

(g) Deep percolation (D_P).

This occurs when the root zone water storage capacity is exceeded by rainfall and irrigation and water is lost below the rootzone.

2.3.4 Using the soil water balance to time irrigations.

Determination of the earliest and latest dates to start irrigating are important in the management of irrigation systems, which are limited in capacity and may be used to irrigate more than one crop. This is often the case in New Zealand, and in other countries where supplemental irrigation is practised. Calculation of the earliest irrigation date is determined by the net irrigation depth to be applied (mm), and the latest by the allowed depletion depth (mm). The difference between the two can be called the irrigation interval. The capacity of the irrigation system will affect the irrigation interval, i.e. it may take several days to irrigate. The calculations are described by Martin *et al.* (1990).

The irrigation cycle is calculated from:

$$t_c = \frac{0.116.A.I_g}{Q} \qquad \textbf{2.7}$$

where, t_c is the cycle time in days, A is the area irrigated (ha), and Q the system flow rate (l s^{-1}). The interval (t_i), between the end of one irrigation and the start of the next (idle time) is calculated by:

$$t_i = \left[\frac{I_n}{ET_c}\right] - 0.116\left[\frac{A.I_n}{Q.E_a}\right] \qquad \textbf{2.8}$$

2.3.5 Errors using soil water balance.

Errors in soil water balance arise from uncertainty of measurements of any of the soil water balance components (Eq. 2.4). Jensen and Wright (1978) investigated the errors and confidence levels that may be expected when predicting irrigations using soil water balance based on ET estimates. They found that the confidence limits were dominated by the component having the greatest uncertainty. They found that the greatest uncertainty was associated with I_n applied on surface irrigated fields, unless excess water was applied.

2.4 Concepts of plant-available water.

Traditional notions of field capacity, permanent wilting point, and available water capacity, usually laboratory-based definitions, have been questioned because of the inaccuracy of transferring their values to the field (Scotter and Clothier, 1986; Hillel, 1990; Ritchie and Amato, 1990).

Comparisons between field and laboratory methods for determining upper and lower limits of water storage have yielded significant differences (Ratliff *et al.*, 1983). Clothier *et al.* (1977) have shown that soils underlain with coarse textured layers will have greater water storage capacity at field capacity than for more uniform soil profiles. Reid *et al.* (1984) also found significant differences between the volume of water extracted by plant roots in the field, and laboratory-estimated available water (AWC).

Therefore, it is more appropriate to use field-measured limits, specifically the drained upper limit (DUL) and lower limit (LL) of plant extractable soil water (PESW). DUL is defined as the water content of a soil after it has been thoroughly wetted and allowed to drain until drainage is negligible (< 1 mm day^{-1}). Whilst the LL is defined as the water content at which plant water uptake apparently ceases, and the plants are visibly stressed. PESW is the difference between the DUL and LL.

2.5 Irrigation scheduling services.

A number of types of service are available in New Zealand and overseas. New Zealand services use soil water balances with soil water depletion measurements using neutron probes. They are operated by private consultants or by Agriculture New Zealand (soon to be privatised).

Overseas, use of similar scheduling services using neutron probes have been described in the UK (Hess, 1990) and USA (Hill, 1990). Services providing ET data from networked meteorological stations for irrigation scheduling have also been described (Ley and Evans, 1990; Hess, 1990).

2.6 Comparison of irrigation scheduling methods.

Whilst a number of irrigation scheduling methods have been described (section 2.3), there has been little reported that compares the relative practical benefits and limitations of different methods.

Fischbach (1981) compared four different irrigation scheduling methods for corn (*Zea mays*) over three years in Nebraska, from the view point of the grain yields and irrigation water applied. The methods used were: (i) a simple water balance using Blaney-Criddle determined ET; (ii) irrigation when available soil water was depleted by 50% using electrical resistance blocks; (iii) "stage of growth" and the "hand feel method" for determining soil moisture (the latter used for "fine tuning"); and, (iv) irrigating, when necessary, on a fixed rotation of 14 days, the "stage of growth" and "feel method" being used to determine when to stop irrigations.

The results showed that there was no significant difference in the grain yields, or amounts of water applied, from the different methods, except in one of the three years when one less irrigation was required for the fixed rotation due to the timing of rainfall. However, deep percolation losses were observed for nearly all the scheduling methods. To counter this, it was recommended that a certain level of soil water deficit should be maintained at irrigation to make more effective use of rainfall and reduce leaching losses.

Camp *et al.* (1988) compared three different scheduling methods from Fischbach (1981) for corn and soybean (*Glycine max*). These were based on: (i) tensiometer soil moisture suction; (ii) evaporation pan; and, (iii) a computer-based soil water balance. Again there were no significant differences between yields or irrigation water applied for the different methods. Excessive irrigation, or rainfall after irrigation, resulting in deep percolation losses was also observed and caused a measured deficiency of potassium in the corn plants.

A comparison has been made of three different commercial irrigation scheduling practices with a computer-based soil water budget model for corn (Field *et al.*, 1988). Three levels of scheduling sophistication were analyzed, they were: (i) soil water measurement using gravimetric soil samples at several depths; (ii) a combination of soil water measurements (taken at several locations and depths in each field using a neutron probe) and ET estimates; and, (iii) a combination of soil water measurements taken to a depth of 300 mm (using a neutron probe) with only one measurement per field, and ET estimates.

Their results showed that there was no significant difference between the commercial scheduling methods. Generally high yields were obtained by all methods. All schedules were calculated to refill the soil to near field capacity. It was estimated that economic returns would have increased if regulated deficit irrigation had been employed.

In the last two cases (Camp *et al*, 1988; Field *et al.*, 1988) irrigation was by centre-pivot, which would ensure reasonably uniform water applications. In the first case (Fischbach, 1981) surface irrigation was used.

From these three different comparisons no conclusions were made regarding the best method for scheduling (of corn). As a result no recommendations were made, except the statements that a) by using a scheduling method it is likely that yields will be improved, and b) that by planning to maintain a deficit in order to use rainfall more effectively, economic returns will be improved and deep percolation and leaching losses reduced.

CHAPTER 3 REVIEW OF SOIL MOISTURE SENSORS UNDER EVALUATION.

This chapter gives an overview of the five soil moisture sensors investigated in the research project.

3.1 Neutron probe

Several reviews have been written on the theory and the practical methodologies for use of the neutron moisture meter, or 'neutron probe'. However little information is provided for practical applications of the neutron probe (Dickey, 1990a). The most notable exceptions to this are Bell (1987) and Greacen *et al.* (1981). More detailed theoretical aspects are reviewed by IAEA (1970).

3.1.1 History.

The proposal to use neutron moisture measurement in soils dates to the early 1950's. J.W. Holmes and the soil physics group at CSIRO Division of Soils developed a portable instrument for field measurement in the mid-fifties (Greacen, 1981).

3.1.2 Theory of operation.

The theory of the neutron probe, i.e. of the emission and 'diffusion' of neutrons into the soil is reviewed by several authors, including: Gardner *et al.* (1991); Gardner (1986); IAEA (1970); and, Goodspeed (1981).

3.1.3 Instrument design.

Simply, the neutron probe consists of: (1) a probe containing a fast neutron source, normally Americium - Beryllium, and a slow neutron detector; (2) a pulse counter, or "ratescaler"; (3) a cable connecting the two; and (4) a transport shield (Figure 3.1).

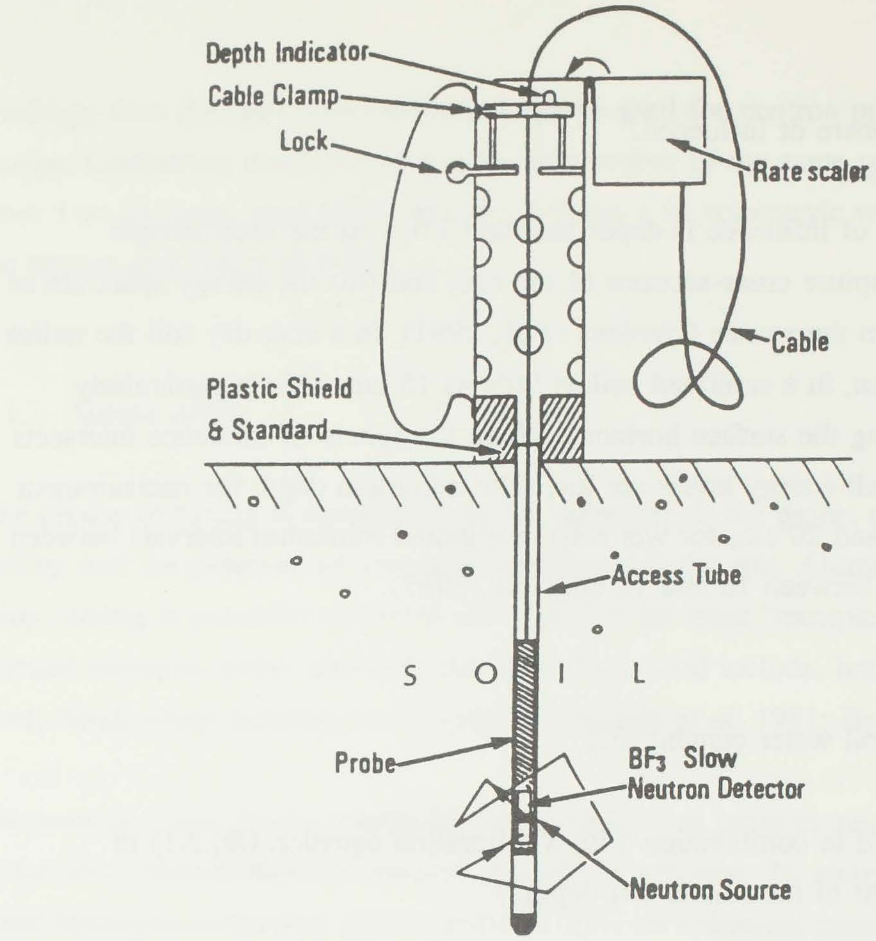


Figure 3.1: Diagram of the neutron probe in use (from Bell, 1987).

The basic principle of the neutron moisture measurement method is that fast (high energy) neutrons are scattered and slowed down by hydrogen nuclei more efficiently than by nuclei of other elements in the soil. The kinetic energy of the neutron is reduced by this thermalisation process from > 1 ke V (fast neutron) to < 0.5 eV (thermal neutron).

Most of the hydrogen found in a soil is present in soil water. According to IAEA (1970) in an average soil about 70% of the moderation is caused by hydrogen atoms (primarily in H_2O); 10% by oxygen; and about 20% by all other elements.

The moderated neutrons returning to the probe are detected by the probe detector, which is sensitive only to thermal neutrons. The detailed arrangement of the source and detector is described by Gardner *et al.* (1991). Electronic signals from the detector are measured by a pulse counter unit and displayed. Ratescalers that measure the number of counts for a preset time, typically between 8 and 64 seconds are now the most common form of counter unit (Gardner *et al*, 1991).

3.1.4 Neutron probe "sphere of influence."

The radius of the sphere of influence is dependent on (i) θ_v, (ii) the macroscopic neutron scattering and capture cross-sections of the soil, and (iii) the energy spectrum of the neutrons emitted from the source (Gardner *et al.*, 1991). In a very dry soil the radius may be as much as 50 cm, in a saturated soil as little as 15 cm. This is particularly important when measuring the surface horizons. When the sphere of influence intersects the surface, neutrons of all energy levels are lost. The minimum depth for measurement is therefore between 15 and 20 cm, for wet soils. Suggested minimum intervals between measurement depths are between 10 and 15 cm (Bell, 1987).

3.1.5 Measurement of soil water content (θ_v).

The neutron count is used in combination with a calibration equation (Eq.3.1) to estimate the water content of the soil at that depth.

$$\theta_v = a.\frac{C_m}{C_s} + b \qquad \textbf{3.1}$$

3.1.6 The use of count standards.

Normally the **count ratio** (C_m/C_s), the ratio of the measured neutron count (C_m) to a **standard count** (C_s) measured in a standard medium, is used in the calibration equation. The standard is normally either water in a large container or another hydrogen rich material (e.g. polythene) which is an integral part of the instrument (its "transport shield").

Count ratios are used because of the effects of instrument drift due to: ageing of components, replacement of components, and as a result of long term decay of the radioactive source. The half life of Americium is 458 years (IAEA, 1970). By using regular standard counts it is possible to monitor the instrument drift and avoid the introduction of instrumental errors into the determination of moisture content. The main disadvantage of using a standard count is that it introduces an additional source of error.

Hodnett and Bell (1991) have assessed the use of the two types of neutron probe standards and concluded that by using a common water standard to "normalize"

readings, then the same soil calibration can be used for neutron probes of the same design. Comparing results from five neutron probes of the same type, ranging in age from 1 to 14 years, they found that the difference in volumetric water content between the probes was less than 0.003.

3.1.7 Access tubes.

The choice of tubing is determined by the diameter of the probe, cost and availability of tubing, and the presence of corrosive substances in the soil. Aluminium, or aluminium alloy, tubing is generally preferred because it is the most "transparent" material to thermal neutrons. Other materials that have been used include, brass, mild and stainless steel, dural, acetyl butyrate and polythene (Prebble *et al.* 1981; Bell, 1987).

The neutron count, hence sensitivity, is reduced when brass or steel tubes are used due to the absorption of thermal neutrons by copper and iron. By contrast polythene and other hydrogen-containing plastic materials give an enhanced count rate compared to aluminium.

3.1.8 Installation procedures.

Careful installation of the access tubes is very important. A number of different methods of access tube installation may be used. Prebble *et al.* (1981) describe nine different methods that have been used and make recommendations as to the best method(s) for a range of soils; some of the practices to be avoided are also listed.

One practice that should be avoided is to prepare an access tube hole using a soil auger (e.g. power auger) of the same diameter as the tube. Reasons for this include: possible deflection of the auger due to stones, or their dislodgement from the side of the hole leaving cavities, and over-sizing of the top of the hole due to the repeated movement of the auger up and down, which would encourage water to move down the side of the hole. Power augers share these same disadvantages and cause much more disturbance (Bell, 1987).

The installation technique adopted by the Institute of Hydrology, U.K. (Bell, 1987) is described below. The equipment used consists of a guide tube, auger, rammer and base plate. The guide tube has an external diameter equivalent to the access tube and the auger fits loosely inside it. The auger is normally 15cm longer than the guide tube (e.g. 1.15m and 1m, respectively). The method involves augering 15cm ahead of the guide tube, i.e. to its full length, then carefully ramming the guide tube to this new depth. Soil is then removed from the guide tube by the auger and a further 15cm ahead of the guide tube is augered. If the guide tube is forced beyond the augered depth soil will be compressed into the tube resulting in distortion of the sides of the hole. A metal base plate (about 50cm x 50cm x 0.5cm with a 4.5cm hole in the middle) is used to minimise ground surface disturbance.

"Method 1" described by Prebble *et al.* (1981) is very similar to the one described above except that the access tube itself is used as the guide tube (the bottom of the tube is sealed after installation). The main disadvantage of this method is that for tubes longer than 1.5 m a ladder, or scaffolding, is required.

3.1.9 Calibration methods.

Calibration against a specific soil is normally achieved by comparing the count ratio (Eq. 3.1 above) with soil water content obtained by the conventional gravimetric method. The relationship between count ratio and volumetric water content (θ_v) is generally linear for the range of moistures of interest in agricultural soils (Dickey, 1990a).

Three main techniques for calibration have been used: (i) theoretical calibration ; (ii) laboratory calibrations using re-packed drums of soil; and, (iii) field calibrations. Greacen *et al.* (1981) have reviewed the merits of these different techniques.

The field calibration technique is the simplest. Greacen *et al.* (1981) recommend a technique described by Bell (1987) which involves installing temporary access tubes close to a permanent tube. Soil samples are taken close to the temporary tube at different depths and their water contents measured. These can be compared to count rates taken prior to destructive sampling. To cover the range of soil moistures a number of subsequent samplings using temporary tubes are required.

Greacen *et al.* (1981) found coefficients of variation for a field calibration of the order of 5% for a "uniform" soil and about 15% for a "variable" soil. For a well conducted drum calibration the coefficient of variation should be less than 2%.

Dickey (1990b) describes another simple, quick field method adopted by the U.S. Soil Conservation Service using a "madera" soil sampler, which minimizes soil compaction, and an auger slightly smaller than the diameter of the access tube to be installed. According to Dickey (1990b) accuracies of within ± 1% of gravimetrically-measured water content is common for a 2 m soil profile.

3.1.10 Factors affecting neutron probe calibration.

As soils will contain hydrogen in forms other than soil water, calibration of the neutron probe for each specific soil type is required. The main factors influencing the calibration are: the volumetric content of constitutional hydrogen, not in soil water but bound in the clay minerals and organic matter; changes in the soil dry bulk density, which affects the concentration of soil atoms other than hydrogen; and certain soil chemical components which can absorb thermal neutrons, for example boron, chlorine and iron are strong absorbers.

3.1.11 Measurement bias and precision.

Kempthorne and Allmaras (1986, p.22) define bias as the deviation of the "statistical true value" from the "scientific true value", whilst precision is the measure of variability of an observation around the "statistical true value".

Bias can be important because it will result in either a systematic over-estimate or under-estimate of soil water content. Errors resulting in bias occur due to:

(1) The use of an incorrect calibration equation. For example, from another soil type. Biases in the intercept and slope will affect estimates of soil water content. Bias may also be introduced by the method of calibration used. A laboratory drum calibration is likely to be more precise than a field calibration. However the drum method may also introduce bias since the soil is sieved and repacked around the

access tube, unlike a field calibration where a hole is drilled into the undisturbed soil.

(2) Installation technique and variation in access tubing. Differences in access tube material, diameter and wall thickness will all introduce some degree of bias. By standardising the tubing bias will be minimised. Poorly installed access tubes can introduce very large error, which is normally greatest at the surface because soil disturbance is most likely to occur here due to poor installation technique (Williams and Sinclair, 1981).

(3) Changes of standard counts over time due to changes in detector electronics with ageing and replacement of components causing instrument drift. By using the count ratio this bias is largely reduced and the loss of precision is negligible (Williams and Sinclair, 1981).

Precision of a measurement is given by the measure of random error. Random error in θ_v from the neutron probe arises from three individual components.

(1) The location component. This accounts for the error due to the heterogeneity of soil water distribution over the site, and is normally the greatest source of random error.

(2) The instrument component. This accounts for the random counting error arising from the randomness of the radioactive decay process, and the random error in detector electronics.

(3) The calibration equation component (Williams and Sinclair, 1981).

The various random error components and measures to reduce them are discussed by Williams and Sinclair (1981). By increasing the number of sites, the location and instrument components will be reduced. Instrument error is unlikely to contribute significantly to the total variance, however precision may be increased by using longer count times. Williams and Sinclair (1981), by analysis of three different and diverse sets of data, found that counts of longer than 30 seconds were unlikely to significantly improve the precision of θ_v measurements.

Methods of error analysis are described by Williams and Sinclair (1981). Bell (1987) describes a method for calculating the random counting error used to determine the minimum counting time required for the minimum required precision.

3.1.12 Irrigation scheduling using the neutron probe.

The use of neutron probes for irrigation scheduling has been described above in section 2.5. A simple scheduling technique which is based on graphic display of neutron probe measurements which has proved accurate is described by Gear *et al.* (1977). No other information was required about the field or crop.

3.2. Time Domain Reflectometry.

The use of time domain reflectometry (TDR) is a relatively recent, but now established method of measuring both θ_v and soil bulk electrical conductivity (Nadler *et al.* ,1991). Topp and Davis (1985a) give a comprehensive review of the theory and use of TDR.

3.2.1 Principle of TDR.

TDR is used to measure the bulk dielectric constant (K) of the soil. Topp *et al.* (1980) showed that water content is the main factor influencing the dielectric constant of soil: K for water is about 80; while for most other soil constituents it is between 3 and 5.

A voltage 'step', or pulse, is generated and propagated along a transmission line into the soil. In terms of spectral content (i.e. in the 'frequency domain', rather than the 'time domain'), this step or pulse can be decomposed into a wide range of frequencies, centred in the microwave region of the electromagnetic spectrum. Metal rods are used to transmit the pulse in the soil (the dielectric medium) and act as wave-guides. The signal is reflected back from the bottom of the wave-guides to the receiver and the time interval between the incident and reflected pulse is measured.

The propagation velocity of the pulse, which is determined by θ_v, is calculated from the time interval and the length (l) of the transmission line.

The dielectric constant K is determined by:

$$K = \left(\frac{ct}{2L}\right)^2 \qquad 3.2$$

where, K is the dielectric constant and c the propagation velocity of an electromagnetic wave in free space.

Topp *et al.* (1980) have shown experimentally that K is highly sensitive to θ_v, whilst there were only slight effects due to soil texture, bulk density, temperature, salinity and hysteresis in the soil moisture characteristic. They used several soils with a wide range of textures, and found that an empirical relationship existed between K and θ_v. Their calibration for mineral soils is:

$$\theta_v = -5.3 \times 10^{-3} + 2.92 \times 10^{-2}K - 5.5 \times 10^{-4}K^2 + 4.3 \times 10^{-6}K^3 \qquad 3.3$$

Here θ_v is an average for the depth of the wave-guides in the soil.

3.2.2 Instrument design.

There are 4 basic instrument components: a timing control unit, a pulse generator, a sampling receiver, and a display module (Figure 3.2). The pulse generator supplies a voltage step with a very fast rise time (10^{-10}seconds). The generated pulse travels past the receiver, along a coaxial cable to a "balun" transformer then into the soil via the metal wave-guides. The balun transformer, an impedance matching transformer, is used to minimise any wave reflection at the junction of the coaxial cable and wave-guides, and hence to maximise the transmission of signal into the soil.

3.2.3 Transmission lines (wave-guides).

Most TDR systems have employed parallel-wire or twin-waveguide transmission lines in the soil and use a balun transformer (Topp and Davis, 1982; Topp and Davis, 1985b). Coaxial transmission lines filled with soil were used for some of the early experimental work (Topp *et al*,, 1980), however they are not practical for field measurement.

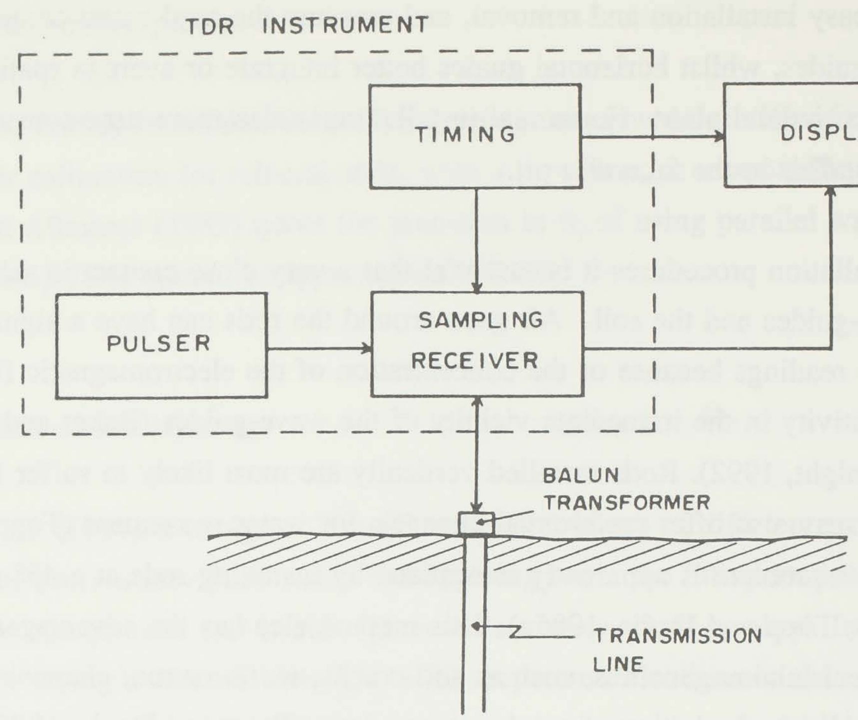


Figure 3.2: A schematic diagram of a TDR probe and its display unit (from Topp and Davis, 1985).

Recently Zegelin *et al.* (1989) have recommended the use of three or four-wire transmission lines which were found to behave much more closely to a coaxial transmission line. They found that this reduced the amount of signal noise experienced using two-wire transmission lines and removed the requirement for a balun transformer. These improved signals permit more accurate and reliable measurement of θ_v in addition to reducing the instrument's cost. The three-wire transmission line is more practical for most applications (Zegelin *et al.* 1989).

Topp and Davis (1982, 1985b) have experimented, with some success, with impedance discontinuities built into the wave-guides to provide profiles of water contents. Problems were observed using these wave-guides in the field: some of the discontinuities were not always detectable from the trace; whilst the method of constructing these lines was both labour-intensive and time-consuming.

3.2.4 Wave-guide installation procedures.

Wave-guides may be installed vertically, horizontally or at an angle to the vertical. The method adopted depends on the measurement requirements. Vertical wave-guides have the advantage of easy installation and removal, and measure the total water content over the length of the guides, whilst horizontal guides better integrate or average spatial variability in the horizontal plane. Horizontal installation is also more time-consuming as the rods are installed in the face of a pit.

In any of the installation procedures it is essential that a very close contact is achieved between the wave-guides and the soil. Air gaps around the rods can have a significant effect on moisture readings because of the concentration of the electromagnetic field and hence of sensitivity in the immediate vicinity of the wave-guides (Baker and Lascano, 1989; Knight, 1992). Rods installed vertically are most likely to suffer from this problem, and may also offer preferential channels for water movement (Topp and Davis, 1985b). This problem is apparently minimized by installing rods at a 45° angle (Topp *et al*., 1980; Topp and Davis, 1985a). This method also has the advantages of crossing any vertical inhomogeneities, such as soil cracks, worm or root channels, and is also less likely to initiate formation of cracks or openings (Topp and Davis, 1985a).

Methods of installing vertical and horizontal lines are described by Topp and Davis (1982, 1985a). In their field evaluation a drill was used to make undersized pilot holes for the vertical brass rods (diameter 12.7 mm), which were then pushed in. However they found that drilling was not necessary for rods of smaller diameter (3 and 6 mm) as soil disturbance is minimal (Topp and Davis, 1985). The optimum spacing between paired wave-guides is apparently 50 mm, whilst the limiting minimum and maximum rod lengths are normally 0.1 and 1 m, respectively (Topp and Davis, 1985a). One commercial TDR instrument, the 'Trase' device (Soil Moisture Equipment Corp.) used in the present study, has minimum and maximum depth limits of 0.15 and 0.7 m.

3.2.5 Sample volume.

The soil volume sampled by TDR is roughly cylindrical with a cross sectional area of 3800 mm^2, with parallel wave-guides 50 mm apart (Topp and Davis, 1985a). However most sensitivity lies in a much smaller cross sectional area of approximately 1000 mm ^{2}, with dimensions of approximately 25 x 65 mm, with sensitivity dropping rapidly from the surface of the rods (Baker and Lascano, 1989). Therefore air gaps immediately adjacent to the rods can have a significant contribution to the measurement error.

3.2.6 Measurement precision.

Topp *et al*. (1980) found that their TDR readings were within ± 2% of measured θ_v using their calibration for mineral soils, with a precision, or repeatability, of ± 1%. Baker and Allmaras (1989) quote the precision in θ_v of using parallel wave-guides and an automated TDR system as approximately 0.6%.

3.2.7 Effect of soil layering.

Nadler *et al*. (1991) investigated the effects of soil layers of different moisture contents on TDR measurements. They found that layering made the interpretation of the TDR trace more complicated and could reduce the accuracy of the method. In the case of a dry soil overlying a wet soil they found that separate reflections in the upper layers were difficult to discern. In the case of a wetter layer overlying a dry layer, readings may give estimates of θ_v that are greater than the actual θ_v. These were extreme cases and are rarely likely to occur under natural conditions (Nadler *et al*., 1991). Theoretical analysis by Morgan (1991) has also shown that TDR moisture readings in soils with strong moisture gradients or layering could be erroneous.

This effect was observed whilst the Trase instrument was being demonstrated in a pot (containing a plant), which had a wet layer of soil overlying a dry layer. Large differences in θ_v were recorded between successive readings. However, on inspection of the TDR signal trace only small differences were observed. It appears that small signal reflections caused by the moisture layering had been erroneously interpreted by the instrument. Manual calculations using visual interpretation of the signal trace resulted in much more precise readings.

3.2.8 Salinity.

The application of TDR for measurement of bulk soil electrical conductivity (and hence estimation of soil solution concentration) has been reported by a number of authors (Dalton and Van Genuchten 1986; Nadler *et al*. 1991; Zegelin *et al*., 1989).

3.2.9 Automation.

Recent developments have been made to allow the automation of TDR systems. Baker and Allmaras (1990) describe two systems for automating and multiplexing measurements using the TDR. One system employs a data logger and the other has a direct link to a personal computer which was programmed to convert a digitised waveform from the TDR.

Wraith and Baker (1991) measuring the root water uptake of a sorghum plant adopted a system which was a combination of the systems described by Baker and Allmaras (1990), using horizontal paired wave-guides, and a datalogger to convert digitised waveforms from the TDR to θ_v.

To date no use of an automated TDR system for irrigation scheduling has been reported, however the potential for an automated irrigation system was noted by Topp and Davis (1985). Recently, commercially available, automated datalogging systems capable of automatic control of irrigation have become available.

3.3 Tensiometers.

3.3.1 Tensiometer operation.

Excellent reviews of the principles of tensiometer operation have been written by Cassell and Klute (1986) and Mullins (1991).

3.3.2 Instrument design.

Figure 3.3 shows the essential components of a tensiometer for field use. The fine ceramic porous cup is connected to an airtight water-filled column and a measuring device: a bourdon gauge, manometer, or pressure transducer, is used to determine the pressure of the water in the column.

Tensiometers are commercially available but may also be easily and cheaply constructed. Details of designs are described by: Cassell and Klute (1986) for bourdon gauge, mercury-water manometer, and miniature tensiometers; Webster (1965) for

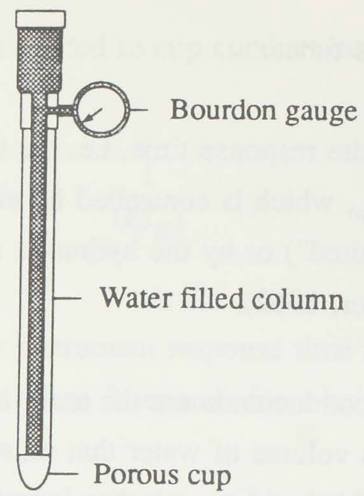


Figure 3.3: Diagram of a bourdon gauge-type tensiometer.

mercury-water tensiometers; and, Mullins *et al.* (1986) for portable, pressure transducer tensiometers.

3.3.3 The principle of tensiometry.

When the tensiometer cup is in hydraulic contact with the soil, water moves between the water column (via the porous cup) and the soil until the (negative) pressure or (positive) suction, s within the porous cup is in equilibrium with the matric potential, ψ_m, of the soil water.

3.3.4 Design Limitations.

The maximum, limiting suction of a tensiometer, in the field, is approximately 85 kPa. Above this suction the water column breaks and no increase in suction will register. Even below this suction dissolved air is released from the water column at high s values. As a result of the accumulation of air the accuracy of s readings is reduced, making it necessary to regularly "purge" the tensiometer to give a more reliable reading. Cassell and Klute (1986) suggest that tensiometers should be inspected for air accumulation at least twice a week and preferably more often, depending on the weather and soil moisture conditions. To help minimize the air accumulation problem tensiometers should be filled with water that has been de-aired, either by boiling or by leaving the water for a few hours in an evacuated container.

3.3.5 Tensiometer response times.

Every tensiometer has a finite response time, i.e. the time it takes for the tensiometer to register a change in soil ψ_m, which is controlled by either the characteristics of the instrument ("instrument limited") or by the hydraulic conductivity of the soil ("soil limited") (Klute and Gardner, 1962).

Gauge sensitivity and cup conductance are the main instrument limiting factors. Gauge sensitivity is defined as the volume of water that must move for a given change in potential. The term "gauge" is used generically; it includes measurement devices such as bourdon gauges, manometers and pressure transducers.

Cup conductance, k, is determined by the cup's pores sizes which affects the rate at which water can transfer between the water column and the soil. The main design limitation for the cup is the pore size. They must be small enough to prevent the movement of air through the cup, whilst giving the cup a high conductivity to respond quickly to changes in soil ψ_m. Cup conductance is defined by:

$$k = \frac{V}{(t\Delta H)} \qquad 3.4$$

V is the volume of water that flows through the cup in time t when there is a pressure difference ΔH. Standard ceramic cups for field use have a conductance of about 3×10^{-9} $m^2\ s^{-1}$ (Cassell and Klute, 1986).

Gauge sensitivity, S_G:

$$S_G = \frac{dh_T}{dV} \qquad 3.5$$

where h_T is the pressure head (m) in the tensiometer fluid. Cassell and Klute (1986) give an example of a bourdon type gauge which has a gauge sensitivity of approximately 2×10^8 m^{-2}.

The tensiometer response time, T_r, is related to cup conductance and gauge sensitivity by:

$$T_r = \frac{1}{(kS_G)} \qquad 3.6$$

Therefore by increasing k and S_G the instrument response time is reduced. Using the examples of k and S_G above, T_r is less than 2 seconds for a bourdon gauge tensiometer.

Towards the upper suction limit of the tensiometer, soil hydraulic conductivity becomes more important, and if the instrument response time is sufficiently small, it may become the determining factor of the response time, i.e. "soil-limited". In most cases the instrument is the limiting factor. The theory of these responses has been investigated by Klute and Gardner (1962) and Towner (1980).

3.3.6 Measurement accuracy.

A mercury manometer tensiometer has an accuracy of approximately ±0.25 kPa. A bourdon gauge tensiometer will often be an order of magnitude different; typically they have scale divisions every 2 kPa. In addition bourdon gauge accuracy may be limited due to friction within the gauge mechanism and from bias introduced with inaccurate zero settings.

3.3.7 Portable Tensiometers.

The performance of this type of tensiometer has been investigated by Mullins *et al.* (1986). They demonstrated that the portable tensiometers can only be accurately used at suctions close to zero because at higher suctions prohibitively long equilibration types were experienced. For example, they found that it might take over two hours for tensiometers to equilibrate at suctions greater than 30 kPa. The response was limited by the time taken for the disturbed soil in contact with the porous tip to re-equilibrate with its surroundings (i.e. a "soil limited" response).

3.3.8 Installation procedures.

Installation procedures are discussed by Cassell and Klute (1986), Webster (1965) and Lord (1989). The most important requirement of the installation procedure is that the porous cup is in good hydraulic contact with surrounding soil. An auger, or spike driven into the soil should be used to make the installation hole. Cassell and Klute (1986) suggest that embedding the cup in a slurry made from soil removed from the bottom of the hole gives a good soil-cup contact. Gaps between the tensiometer column and soil should be backfilled using the excavated soil. At the soil surface soil should be mounded slightly around the tensiometer to prevent water running down the tensiometer column.

Maintenance procedures are described by Cassell and Klute (1986). A hand vacuum pump can be used to purge tensiometers in the field. A suction of between 60 and 80 kPa should be applied with the pump to allow air bubbles to rise to the top of the tensiometer. A period of about 1 to 2 hours should be allowed after purging to allow for equilibration after the hydraulic disturbance introduced into the soil water (Cassell and Klute, 1986).

3.3.9 Automatic irrigation systems.

Commercially available pressure transducer systems for triggering irrigation are now available (Lok, 1992). In particular drip irrigation lends itself to control using soil moisture suction sensors, such as tensiometers (Hodnett *et al.*, 1990).

3.3.10 Irrigation scheduling using tensiometers.

Tensiometers have been widely used for irrigation scheduling.
Haise and Hagan (1967) made practical recommendations for scheduling a range of crops, including the required number of sensors and installation depths and tables of suctions at which to irrigate.

3.4 Electrical resistance sensors.

Recent notable reviews on the theory and use of electrical resistance sensors for measuring soil moisture status include those of Campbell and Gee (1986), Mullins (1991), and Wellings *et al* (1986). The measurement of the electrical resistance of a soil using two electrodes pushed directly into the soil to determine its water content was proposed nearly a century ago. Over the last 50 years the method has developed and the electrodes are now embedded in a porous medium which is placed in hydraulic contact with the soil.

Electrical resistance sensors provide a measure of the soil water suction because at equilibrium the sensor matrix and soil share the same matric potential (ψ_m). They do not provide a direct measure of soil water content, because different soils have different soil moisture characteristics.

Several types of electrical resistance sensor have been manufactured. The use of gypsum was first proposed by Bouyoucos and Mick (1940); it can be made more durable by treatment with nylon resin (Bouyoucos, 1953). Other porous materials used include nylon fabric and fibre-glass. Gypsum has generally been preferred for the matrix material because it can be easily cast into shape, and because the water in the block becomes saturated with $CaSO_4$, buffering the solution in the block against any changes in the ionic concentration of the soil water. Sensor electrodes are usually stainless steel and are normally parallel rectangular, or concentric cylindrical in configuration (Figure 3.4).

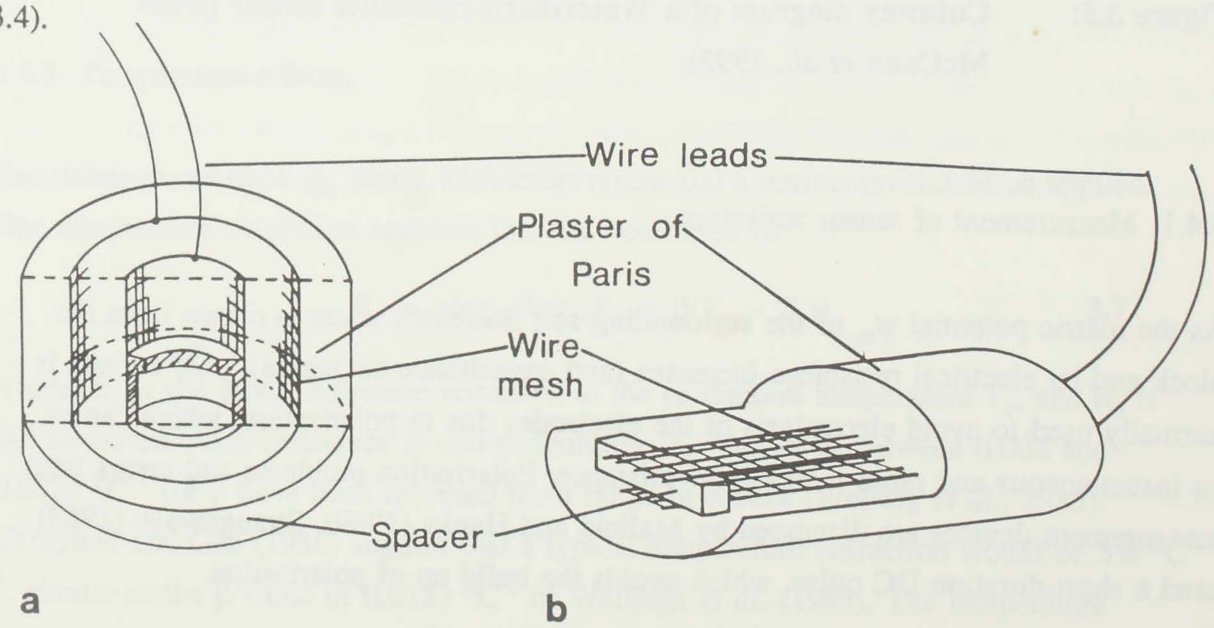


Figure 3.4: **Cutaway diagrams of a) a concentric cylindrical electrode gypsum block, and b) a parallel rectangular electrode gypsum block (from Wellings *et al.*, 1986).**

Recently a different design of resistance sensor the 'Watermark 200', has been manufactured by the Irrometer Inc. Co. This uses a loose graded sand matrix held in place by a porous casing, and gypsum component in the matrix for buffering (Figure 3.5). Another similar design with thin stainless steel casing, for better manufacturing uniformity, has been reported but is not yet commercially available (Shock and Barnum, 1992). The following review will concentrate on the gypsum block and the Watermark type sensor.

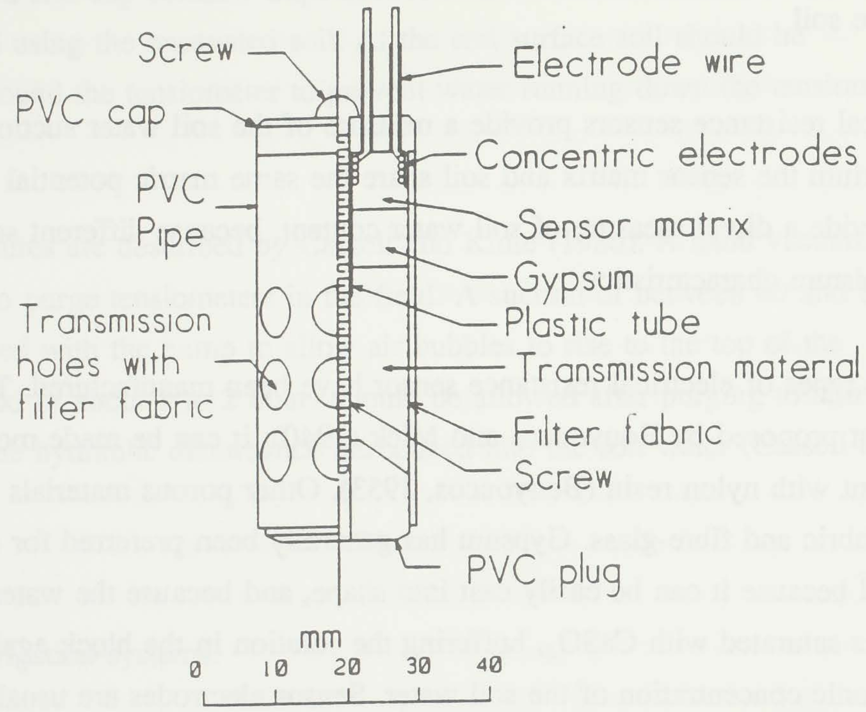


Figure 3.5: Cutaway diagram of a Watermark resistance sensor (from McCann *et al.*, 1992).

3.4.1 Measurement of sensor resistance.

As the matric potential ψ_m of the surrounding soil decreases water is drawn from the block and its electrical resistance increases (and capacitance decreases). AC current is normally used to avoid electrolysis of the electrodes due to polarisation, which causes an instantaneous and rapid increase in resistance. Polarisation problems and errors with measurement devices are discussed by Malicki and Hanks (1989). Strangeways (1983) used a short-duration DC pulse, which avoids the build up of polarisation.

Hand-held meters are available commercially or may be constructed. Measurement circuits have been described by Fowler and Lopushinsky (1989) and Goltz *et al.* (1981).

Cary and Fisher (1983) used microprocessors to measure and store resistance readings and described the use of a programmable calculator to schedule irrigations.

Electrical resistance sensors can be easily datalogged. Datalogging circuits are described for the use of gypsum blocks with the Campbell Scientific CR10 (CR10 operators' manual). Campbell's datalogger software has a dedicated instruction for calculating ψ_m from the measured resistance of their own blocks. A datalogging system that measured a total of 384 Watermark sensors was used to measure ψ_m in the rootzone of irrigated and non-irrigated peaches (Armstrong *et al.*, 1987).

3.4.2 Sensor hysteresis.

Hysteresis occurs with the porous sensors as it does in the soil. However the hysteresis curves of the sensor and the soil are unlikely to be matched. Therefore, if calibrations based on a drying curve are used for calculation of ψ_m on a wetting curve, the errors may be considerable and the variation between blocks unpredictable (Tanner and Hanks, 1952). Hysteresis problems have been noted for gypsum blocks (Cary, 1981) and Watermarks (McCann, *et al.* 1992) under transient soil moisture conditions when irrigation was insufficient to wet-up the sensors completely. If the blocks are completely re-wetted and the blocks are measured for the same part of the wetting and drying cycle for which they are calibrated, this should not be a problem.

3.4.3 Temperature effects.

Resistance at constant ψ_m varies with temperature and a correction should be applied. One temperature correction equation that has been used is:

$$R_c = alog_{10}[\log_{10}R_s + \beta(T_s - T_c)] \qquad \textbf{3.7}$$

where, R_c is the block resistance corrected to the calibration temperature T_c, and R_s is the measured block resistance at soil temperature T_s. Values of between 0.002 and 0.0123 °C^{-1} for β have been recorded for a range of blocks (Welling *et al.*, 1985). Campbell and Gee (1986) suggest that a typical temperature correction would be 3% °C^{-1}, similar to the β value of 0.0123 °C^{-1} of Wellings *et al.* (1985). The temperature correction for the Watermark is approximately 2.8 to 3.3% °C^{-1} (McCann *et al.*, 1992).

3.4.4 Gypsum dissolution.

As described above, the dissolution of gypsum is important because of its buffering against the effect of changes in soil solution concentration. It also means that the block has a finite lifetime. Increased dissolution occurs with increasing soil moisture, and low pH. A block may last from under a year to 10 years depending on the conditions (Bouyoucos, 1953). Dissolution and changes to the properties of the matrix is likely to cause some drift in calibration.

Unlike the gypsum block the Watermark synthetic-sand matrix will not dissolve, however it is likely that the gypsum tablet in the sensor will. Sensor calibration drift has been reported by Armstrong *et al.* (1987) for sensors in the soil over three years. Greatest drift occurred in the sensors subjected to the most drying cycles.

3.4.5 Measurement range.

Gypsum blocks are insensitive to changes at high ψ_m. The value of the upper working limit varies between blocks but is generally between -30 and -50 kPa. Wellings *et al.* (1985) suggest that their use is best restricted to between -70 kPa to -1 Mpa. The relationship between resistance and ψ_m over this range is approximately linear on a log-log scale.

Watermark sensors are designed, by contrast, to be most sensitive towards high potentials (i.e. at lower suctions). The manufacturer claims a range of between -10 and -200 kPa. The manufacturer's calibration is also linear on a log-log scale (Watermark operators' manual, Irrometer Inc. Co.).

3.4.6 Sensor response times.

The response time of these sensors is a function of the suction gradient and hydraulic conductivity within the soil, and within the sensor. Therefore response times will vary between different sensors.

3.4.7 Sensor Calibration.

Since sensor electrical resistance is an indirect measure of ψ_m, some form of calibration is required, whether it is in units of ψ_m (e.g. kPa) or simply a relative scale. For gypsum blocks, calibration using the pressure plate apparatus is the easiest method (Wellings *et al.*, 1985; Campbell and Gee, 1986). Wellings *et al.* (1985) found that a minimum of three points (-0.6, -1.5 and -4 bar) were required for a calibration curve for their gypsum blocks. The calibration is in the form:

$$\psi_m = alog_{10}[a.\log_{10}R_c + \log_{10}b] \qquad \textbf{3.8}$$

where, a and b are constants unique for each block. This equation will be referred to again in the Results section.

Non-linear calibrations of ψ_m versus resistance and temperature data have been developed for the Watermark sensors (Armstrong *et al.*, 1985; Thomson and Armstrong, 1987; Spaans and Baker, 1992; McCann *et al.*, 1992). The manufacturer's calibration is nearly linear. Comparison of the different calibrations yields different results, possibly because of a change in the manufacture of the sensors (McCann *et al.*, 1992). Calibrations have been performed using the pressure plate system (McCann *et al.*, 1992) and pressure plate extractor (1 bar) (Thomson and Armstrong, 1987), and with tensiometers in soil containers (Armstrong *et al.*, 1985 and Spaans and Baker,1992).

3.4.8 Sensor measurement errors.

The principal sources of error affecting measurement of ψ_m from sensor resistance have been identified by Wellings *et al.* (1985) as follows:

(i) The application of a single calibration curve to all sensors.
(ii) Calibration drift.
(iii) Assumption of an incorrect calibration equation.
(iv) Hysteresis.
(v) Incorrect measurement of block resistance.

3.4.9 Installation requirements.

Procedures for field installation have been described by Richardson and Mueller-Beilschmidt (1988) and Wellings *et al.* (1985). The blocks should be saturated prior to installation. To ensure good contact between the soil and sensor is achieved, the use of a soil slurry around the block to improve soil-sensor contact has been recommended (Wellings *et al.* 1985).

A method for installing several gypsum blocks at a range of depths in a pvc pipe with "windows" cut into it has been tried. This allows the easy recovery of the blocks from the site (Wellings *et al.*, 1985). No difference was found between ψ_m measured with blocks installed by this method, and conventionally installed ones.

3.4.10 Field use of electrical resistance sensors.

(i) Irrigation scheduling.

Cary (1981) found that the accuracy of scheduling with gypsum blocks compared favourably with climate methods. One method has been described which uses Watermark sensors in conjunction with a climate-based method to monitor and adjust soil water depletion (Tyson and Curtis, 1990). A simple guide aimed at the grower has been produced by Richardson and Mueller-Beilschmidt (1988) explaining the benefits and costs of using gypsum blocks, and a method of scheduling using them. Between US$25 and $165 per acre savings in water cost and increase of yield value has been reported using gypsum blocks, compared with non-scheduling (Richardson *et al.*, 1989; see section 2.1c).

(ii) Automation of irrigation systems.

Automatic controllers have been designed for use with the Watermark, to enable automatic control of landscape irrigation systems (Pogue, 1990). Thomson and Threadgill (1987) suggest that the Watermark would be a good substitute for tensiometers which were used in a design which controlled and scheduled irrigations for centre-pivot systems. As described above, electrical resistance sensors can be easily datalogged. For this reason they have also been marketed with commercially available automatic weather stations.

CHAPTER 4 METHODS AND MATERIALS.

4.1 Introduction.

The overall objective of the field trial was to evaluate the sensor characteristics, assessing some of their benefits and limitations, and to aid determination of optimum practical installation pattern and field usage. Results from the trial and from the review of the sensors (Chapter 3) will be discussed in Chapter 5, where the sensor characteristics relevant to irrigation scheduling will be summarised.

The sensors investigated are shown in Table 4.1.

Table 4.1: The soil moisture sensors.

Sensor:	Model:	Manufacturer:
Neutron probe (Plate 1)	3330 series	Troxler Laboratories, Research Triangle Park, NC.
TDR (Plate 2)	Trase	Soilmoisture Equip. Corp., Santa Barbara, Calif.
Tensiometers (Plate 3)	Irrometer "R" and 2725 series "Jet Fill"	Irrometer Co. Inc., Riverside, Calif. Soilmoisture Equip. Corp., Santa Barbara, Calif.
Gypsum blocks (Plate 4)	"Waterwise"	Electronics Unlimited, Sacramento, Calif.
Watermarks (Plate 5)	"200"	Irrometer Co. Inc., Riverside, Calif.

Plate 1: Neutron probe manufactured by Troxler Laboratories.

Plate 2: 'Trase' TDR probe manufactured by Soilmoisture Equipment Corp.

Plate 3: Tensiometers: a) 30cm 'Irrometer' manufactured by Irrometer Co. Inc. and b) 'Jetfill' manufactured by Soilmoisture Equipment Corp.

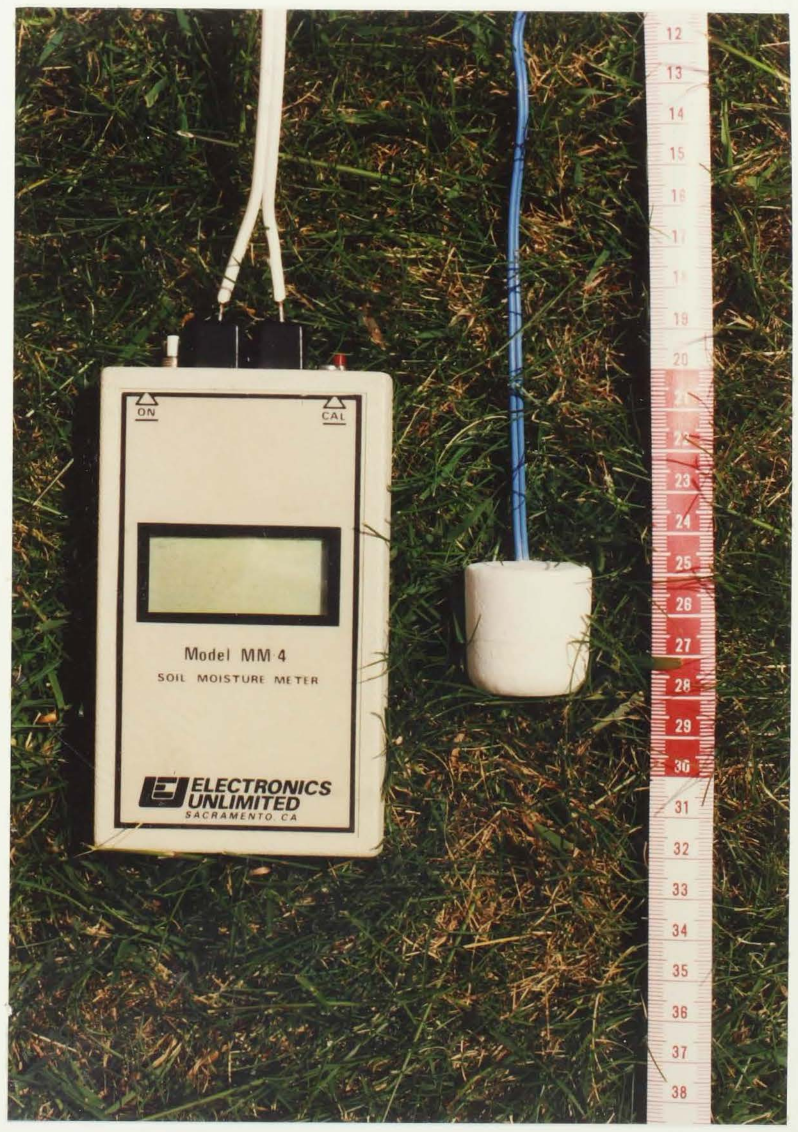


Plate 4: 'Waterwise' gypsum block and meter manufactured by Electronic Unlimited.

Plate 5: "Watermark 200" electrical resisitance sensor and meter manufactured by Irrometer Co. Inc.

4.2 Field evaluation of the sensors.

The five types of soil moisture sensor were installed in a single plot, with threefold replication of sensor arrays within the plot. All were subject to the same wetting and drying cycle treatments. This avoided some of the problems, associated with temporal and spatial variations due to rainfall, irrigation, and soil type, which have characterized other evaluations (Fischbach, 1981; Field *et al.*, 1988; and, Camp *et al.*, 1988).

The objectives of the field trial were as follows.

(i) To evaluate the main practical benefits and limitations of the sensors:

a) the optimum measurement depth(s), the number of sensors required, and the optimum measurement intervals; and,

b) the range and response times of the sensors in field practice.

(ii) To assess the effect of measurement variability within each type of sensor group.

4.2.1 The field site.

The field site was located at Lincoln University, Canterbury, on a Templeton fine sandy loam soil, in block D2. It was selected because it had no obvious relief which might cause problems of non-uniform wetting, and it had a full rye-grass, white-clover cover which would ensure potential evapotranspiration and hence maximum drying of the soil profile. A perennial crop cover also allowed measurements throughout the year. Table 4.2 gives a very basic description of the soil textures in the profile which were taken from a pair of auger holes adjacent to the proposed site.

Table 4.2: Soil textural description.

Depth (cm):	Texture:
0 to 30	Fine sandy loam
30 to 95	Sandy loam
95+	Gravels

A detailed description of the profile was made after all the sensor measurements were completed, when the site was excavated in March 1993 (see below, sections 4.5 and 5.1).

A mobile rain shelter (Plate 6), approximately 4 m x 4 m, was installed and used to cover the field plot when rain was expected. Its walls were made from wind break cloth, which allowed air movement through the mobile structure.

The plan of the sensor installations is given in Figure 4.1 and the installation depths are described in Table 4.3. Each sensor, access tube or wave-guide pair was replicated three times, for all depths of installation.

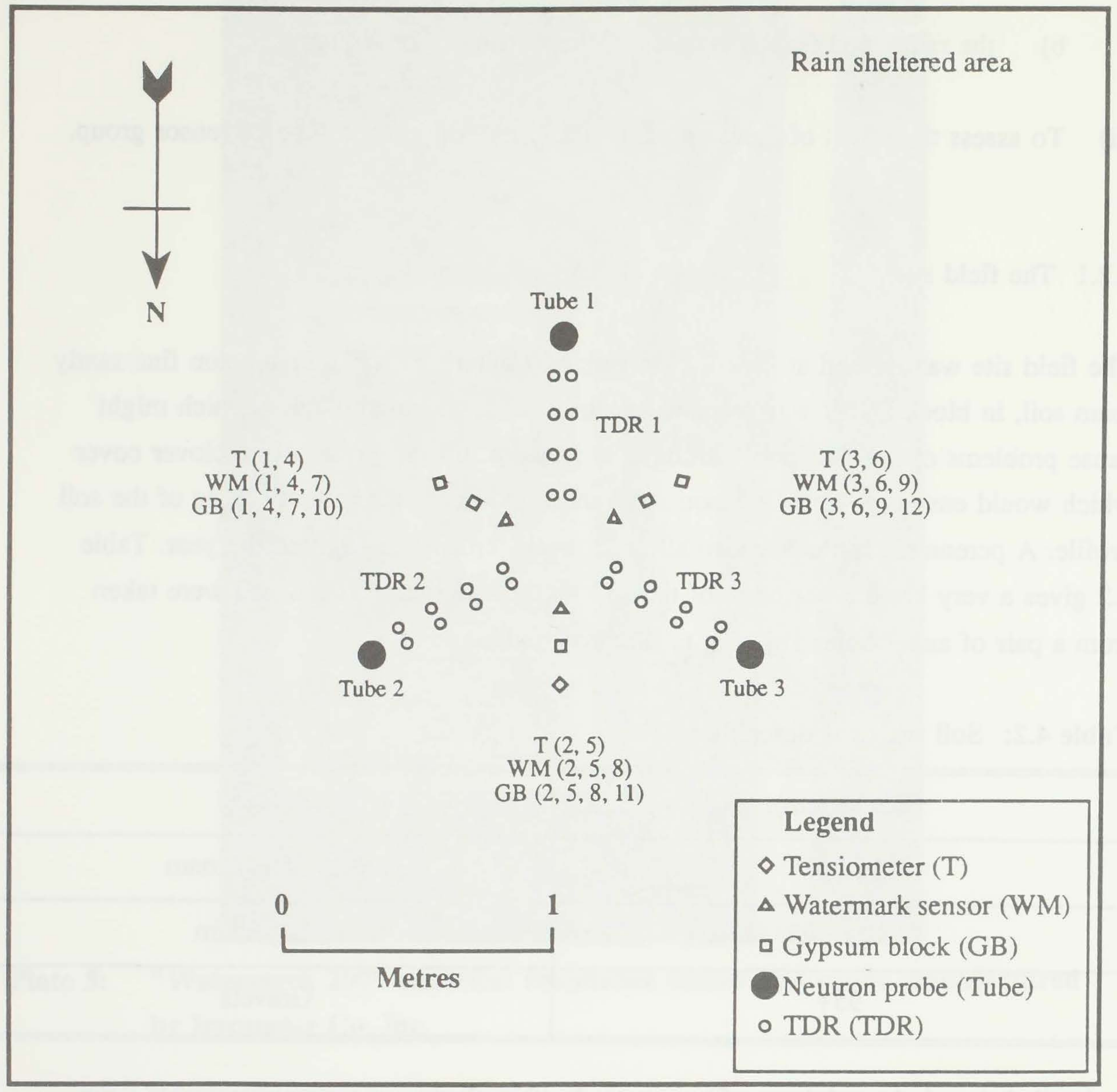


Figure 4.1: Plan of sensor installations in the field plot.

Table 4.3: Sensor measurement depths.

Sensor measurement depths (cm)					
Thermistors	Gypsum blocks	Watermark sensors	Tensiometers	Neutron probe	TDR
15	15	15		15 (minimum)	0 to 15
30	30	30	30	10 cm increments	0 to 30
	45				0 to 50
60	60	60	60	65	0 to 70

Plate 6: The field plot and rain shelter.

The measurement depths used (Table 4.3) were selected for the following reasons.

(1) Rye-grass and clover have effective rooting depths of approximately 50 cm when well watered.

(2) The Trase TDR has minimum and maximum waveguide lengths of 15 and 70 cm, respectively (Trase operators manual).

(3) Attempted measurement of the surface layers with the neutron probe (0 to 15 cm in wet soil) would result in anomalous measurements without special surface calibration (see section 3.1.4).

(3) TDR measures average θ_v over the length of the wave-guides, therefore several wave-guide lengths were required to (a) check the performance of the instrument over a range of depths, and (b) assess the ability of the probe to differentiate moisture contents between different depth layers.

(4) The optimum spacing of neutron probe readings is 10 to 15 cm (Bell, 1986).

(5) This number of sensors was believed to be sufficient to enable the evaluation of the optimum number and depths for practical irrigation scheduling.

(6) The lengths of locally available commercial tensiometers were 30 and 60 cm.

4.3 Sensor installation.

4.3.1 The neutron probe.

The access tubes were installed by the method described by Bell (1986), (section 3.1.8).

Installation equipment (Plate 7) included:

1. Guide tube (1.5 m).
2. Auger (15 cm longer than guide tube).
3. Wooden mallet.
4. Tommy bar.

4.3.2 TDR wave-guides.

The wave-guides were installed according to the manufacturer's instructions (SoilMoisture Equip. Corp., 1990).

Installation equipment (Plate 8):

1. "Installation tool".
2. Alignment blocks.
3. Rubber mallet.

In moist, soft soil, short wave-guides can be easily pushed in using the wave-guide handle. For soils that are compacted, cemented, or very dry, and when using long wave-guides, the manufacturer's installation tool and rubber mallet should be used. To keep the wave-guides parallel, an alignment tool is used.

4.3.3 Tensiometers.

Tensiometers were installed using the method described by
Cassell and Klute (1986) and Lord (1989), using an auger and embedding the porous cup in a slurry made from the soil removed at that depth, (section 3.3.8).

4.3.4 Electrical resistance sensors.

Both gypsum blocks and Watermark sensors were pre-soaked overnight prior to installation.

Installation equipment:

1. Auger.
2. PVC pipe (for pushing in sensors).
3. Slurry container.

The sensor leads were fed through the PVC pipe and lowered into the augered hole by their leads. The pipe was used to gently push the sensor to the bottom of the hole and was also graduated to measure the installation depths. A slurry was mixed from soil removed from each depth at which the sensors were to be installed, then poured down the auger hole around the sensor. Dry soil was then tamped over the sensor. Several sensors were installed in the same auger hole in this manner.

4.3.5 Thermistors.

As the calibration of the electrical resistance sensors is temperature-dependent, simultaneous measurement of soil temperature was considered important. Thermistors were therefore installed as follows: three at 15 cm depth, as temperature fluctuations were likely to be greatest there; one at 30 cm and one at 60 cm. These depths

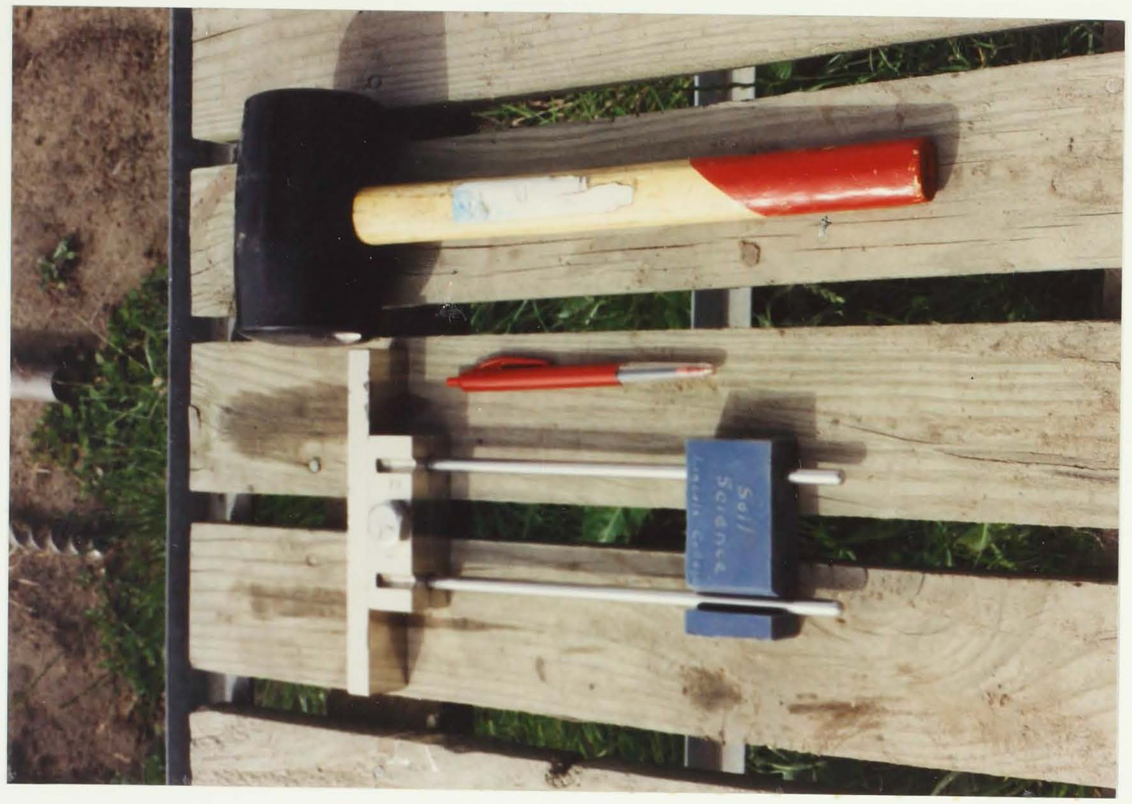


Plate 8: TDR wave-guide installation equipment - auger, guide tube and mallet.

Plate 7: Neutron probe access tube intallation equipment.

correspond with the installation depths of the electrical resistance sensors (except for the gypsum blocks installed at 45 cm).

4.4 Neutron probe calibration.

The calibration used (Eq. 4.1) was locally derived for a Wakanui silt loam, using a standard water count (Greenwood, 1989).

$$\theta_v = 0.769\frac{C_m}{C_s} - 0.033 \qquad 4.1$$

4.5 Measurement intervals.

Regular measurements were taken over the duration of the field trial. Typically the neutron probe and TDR measurements were taken once a week.

The number of tensiometer readings ranged from once a week at times of low potential evapotranspiration to three times a week when potential evapotranspiration was high.

Outputs from the electrical resistance sensors and thermistors were recorded daily, using a Campbell Scientific CR10 datalogger and AM32 multiplexer. More frequent readings were taken for periods during the trial, however it was decided that the information gained from analysis of daily readings was sufficient for sensor evaluation. Manual measurements using the hand-held meters supplied by the sensor manufacturers (Plates 4 and 5) were taken periodically for calibration against the datalogger resistances.

4.6 Logging the electrical resistance and thermistor sensors.

All the electrical resistance sensors were connected to a CR10 datalogger via an AM32, 32 channel multiplexer (both manufactured by Campbell Scientific, Inc., USA), (Plate 9). The thermistors were connected directly to the datalogger. Wiring diagrams for all the sensors are shown in Figures 4.2 and 4.3.

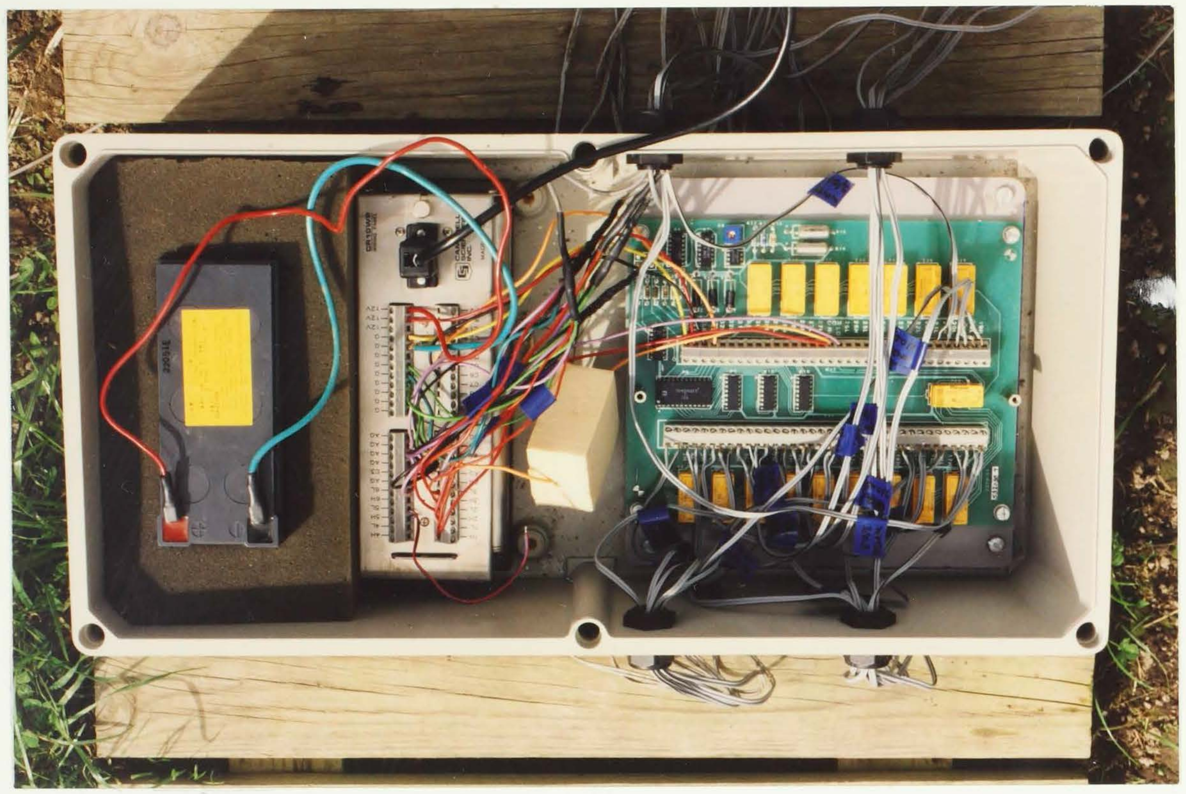


Plate 9: CR10 datalogger and AM32 multiplexer in environmentally-sealed box.

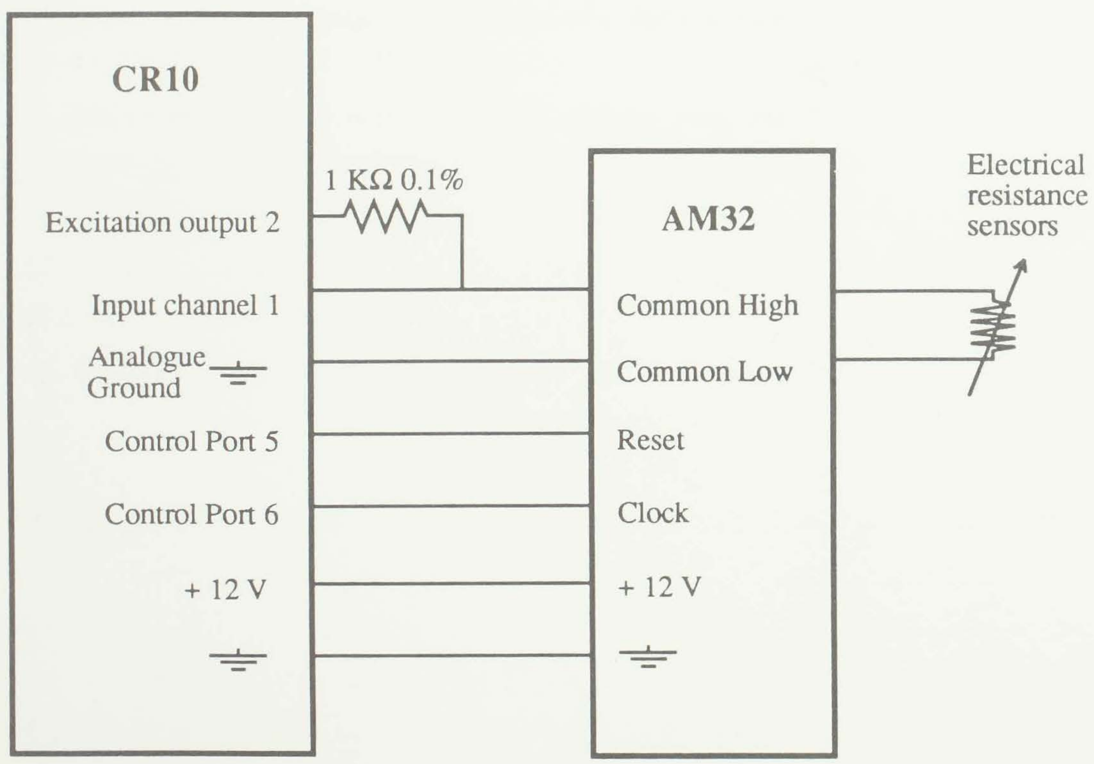


Figure 4.2: Wiring of the electrical resistance sensors to the CR10 datalogger and AM32 multiplexer.

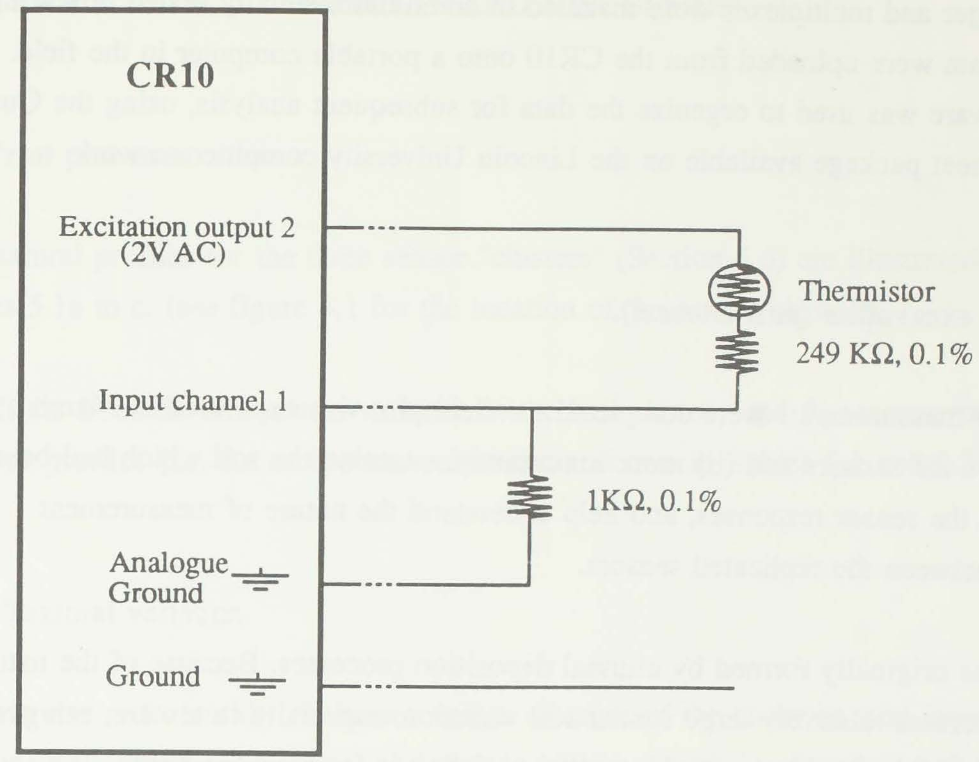


Figure 4.3: Wiring of the thermistors to the CR10 datalogger.

The datalogger programs (Appendix 1) were written using the PC208 software supplied by the logger manufacturer (Campbell Scientific, Inc), then downloaded to the datalogger.

The 21 soil moisture sensors were measured using a half bridge circuit, completed with a 1 kΩ resistor (Figure 4.2). A 250 mV AC excitation was used to avoid polarisation of the electrodes. Voltage measurements were converted to resistances by a half-bridge transform instruction.

A loop instruction was required to measure the multiplexed sensors, resetting the AM32 for each measurement.

Five thermistor sensors were made up within the Soil Science Dept. at Lincoln University, to the specifications of a Campbell Scientific 107 probe, thus enabling the use of a specific CR10 instruction (see Appendix 1). This instruction converts a single-ended voltage measurement into °C, using a fifth order polynomial. The thermistor circuit diagram is shown in Figure 4.3. The overall accuracy of these sensors is typically ± 0.2° C (Campbell Scientific, Inc.).

The datalogger and multiplexer were installed in an environmentally sealed box at the field site. Data were uploaded from the CR10 onto a portable computer in the field. The PC208 software was used to organize the data for subsequent analysis, using the Quattro Pro spreadsheet package available on the Lincoln University computer network.

4.7 Sensor excavation (*post mortem*).

After sensor measurements were completed the field plot was excavated in March 1993 to (i) remove the sensors and (ii) more importantly, examine the soil which had been determining the sensor responses, and help understand the nature of measurement variability between the replicated sensors.

This soil was originally formed by alluvial deposition processes. Because of the nature of these processes relatively large spatial soil variation, especially in texture, can occur in these soils. Visual evidence of this spatial variation is found at the Templeton soil pit at Lincoln University, approximately 50 m north of the trial plot (the soil profile shown in Plate 3 is from this pit). Previous studies on Templeton soils have shown that variation in soil moisture content and bulk density may be expected, the degree of variation increasing with depth (Di and Kemp, 1989).

To attempt to characterize the heterogeneity of the soil surrounding the sensors, bulk density and gravimetric soil moisture measurements were taken. The core samples used were 8.6. cm diameter by 6 cm high with a total sample volume of 348.5 cm^3. Two samples were taken at depths of 15, 30, 45, and 60 cm adjacent to each sensor "cluster", or replicate set, of tensiometers, gypsum blocks and Watermarks (see Figure 4.1). Therefore, a total of six samples were taken for each depth within the plot. The Genstat statistical package on the Lincoln University VAX was used for analysis of variance.

To determine whether soil textural variations had influenced changes in soil moisture, and hence influenced changes in inter-sensor variability, changes in texture (determined by hand) around the sensors were noted and soil profiles drawn for each cluster. Careful note was also made of the sensor-soil contact: (i) to assess the effectiveness of the soil slurry and (ii) because the suction sensors and the TDR may be affected by poor contact.

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Trial plot excavation.

Soil textural profiles for the three sensor "clusters" (Section 4.6) are illustrated in Figures 5.1a to c. (see figure 4.1 for the location of the sensor clusters).

The results from the analysis of variance of the bulk density and θ_v measurements for the three profiles (i.e. for each sensor cluster) are shown in Tables 5.1 and 5.2.

5.1.1 Textural variation.

The irregular and often discontinuous nature of some of the horizons, and interposed bands, indicates there was spatial variation in texture, which increased with depth. See the profile sketches (Figures 5.1a to c); and Plate 10 which clearly shows the bands within the BC horizon in profile 1 (Figure 5.1a), that occur below approximately 60cm. Note the tensiometer cup (T4) is installed in one of these harder, finer textured bands. Most textural spatial variability occurs below approximately 50cm. Therefore soil spatial variability is most likely to have the greatest influence on sensor measurements below this depth.

The layering (see Figures 5.1a to c and Plate 10) in the BC horizon is likely to affect the water movement and storage in this horizon. These layers (or bands) within the horizon had a greater content of finer textured material, which was harder in consistence, less porous and therefore likely to be less permeable to water movement.

Textural layer geometry is also likely to have had an important influence on water movement. The dipping nature of some of the horizon boundaries and irregular nature of the finer bands indicate the non-uniform nature of layer stratification as a consequence of alluvial deposition. The finer less permeable layers are likely to limit water movement between the more transmissive layers (see section 5.2.2).

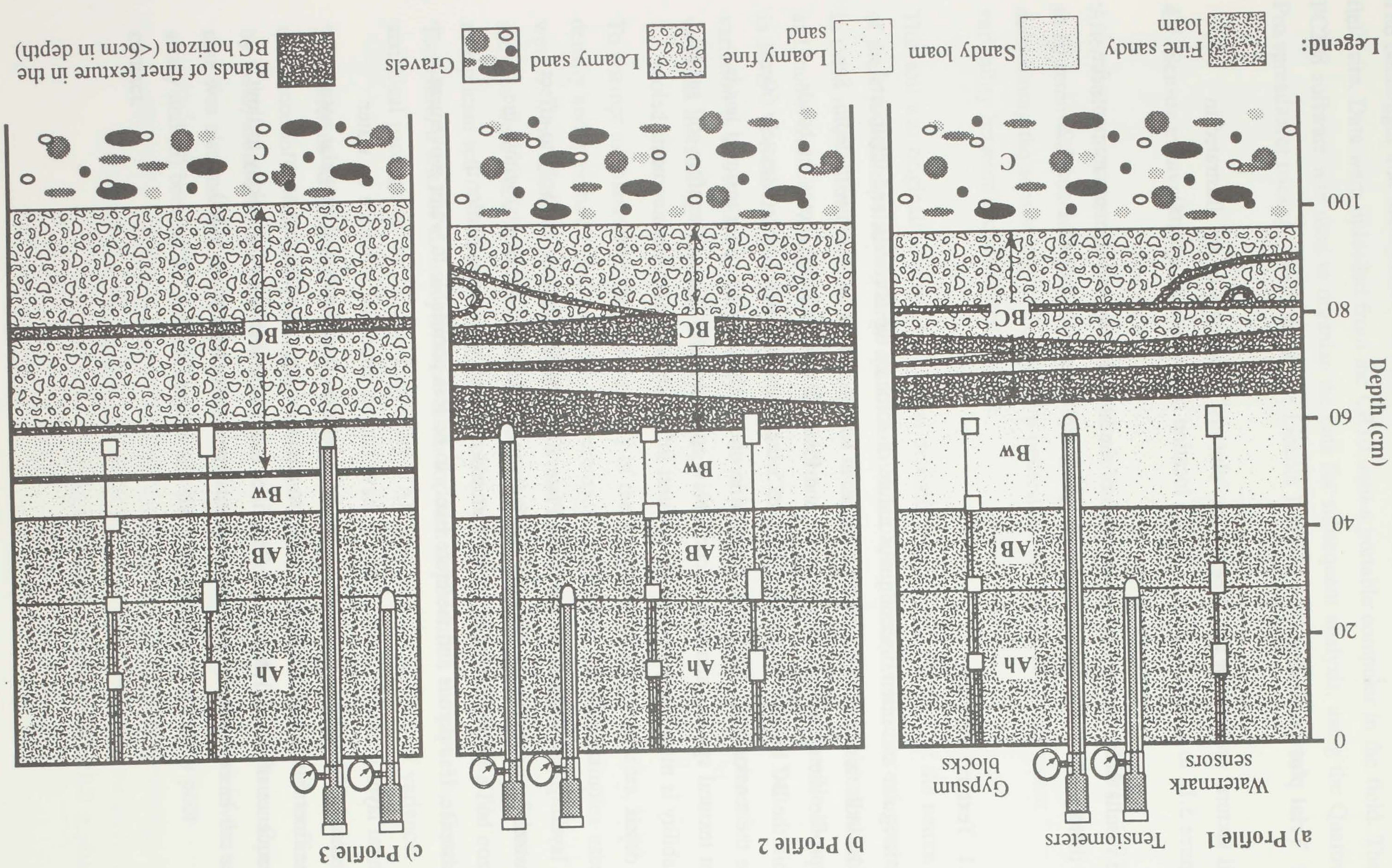


Figure 5.1: Soil textural profiles for three sensor 'clusters' (tensiometers, Watermark sensors and gypsum blocks) within the field plot.

Table 5.1: **Comparison of the bulk density (Mg m^{-3}) measurements for the three "sensor profiles". The soil is a Templeton fine sandy loam.**

Depth (cm)	Profile 1		Profile 2		Profile 3		Mean	Standard deviation	C.V.(%)	Significance
12 - 18	1.2	1.3	1.4	1.19	1.31	1.22	1.27	0.08	8.0	n.s.
27 - 33	1.27	1.26	1.3	1.4	1.16	1.16	1.26	0.09	3.3	**
42 - 48	1.21	1.3	1.28	1.26	1.26	1.41	1.29	0.07	5.6	n.s.
57 - 63	1.3	1.5	1.38	1.54	1.39	1.54	1.44	0.10	8.4	n.s.

**significant at P<0.05; n.s., not significant. 'Significance' refers to the difference between the three profiles.

Table 5.2. **Comparison of gravimetrically measured θ_v (%) for the three "sensor profiles".**

Depth (cm)	Profile 1		Profile 2		Profile 3		Mean	Standard deviation	C.V.(%)	Significance
12 - 18	6.6	7.6	8.0	6.9	8.5	8.6	7.7	0.8	7.9	n.s.
27 - 33	8.8	8.6	9.9	10.7	9.1	10.0	9.5	0.8	5.2	n.s.
42 - 48	6.3	6.5	6.6	7.9	8.9	10.0	7.7	1.5	9.1	**
57 - 63	7.4	11.6	14.0	17.8	18.1	18.3	14.5	4.4	15.9	*

**significant at P<0.05; *significant at P<0.1; n.s., not significant. 'Significance' refers to the difference between the three profiles.

Plate 10: Tensiometer at 30 and 60cm installed in profile 1 (Figure 5.1a). The darker bands of finer texture within the BC horizon are visible below c.60cm.

5.1.2 Bulk density measurements.

There were no significant differences between the three profiles except at the 27-33cm depth. A hard layer at approximately 30cm, the boundary between the Ap and AB horizons was encountered whilst excavating the pit. It is suggested that the differences in bulk densities between the profiles at this depth may be a result of incomplete formation of a plough pan.

As expected the bulk densities increased with depth. These figures show good agreement with those measured by Di and Kemp (1989), also in a Templeton soil. They recorded bulk densities of 1.26 and 1.49 Mg m^{-3} at depths of 20 to 25cm, and 55 to

60cm, respectively. They also found increasing variation in bulk density measurements moving from the shallower to the deeper horizon.

5.1.3 Soil moisture measurements.

High coefficients of variation in θ_v measurements below 33cm depth were not unexpected. Large variation in moisture content had been recorded across the plot by all the sensor types below approximately 50cm depth. This is a result of lateral flow from the edge of the field plot (see section 5.2.2). As a result of soil drying within the plot covered by the rainshelter, the soil was at a lower water potential than the surrounding soil. Therefore water tended to move into the plot as a result of the water potential gradient.

It is also hypothesised that soil water tended to move in to the plot from the western edge within the relatively thicker, coarser layers (Profile 3, Figure 5.1c) which would transmit water most easily when saturated. High moisture contents were also noted in these layers whilst hand texturing. In addition, unsaturated gravels underlying the soil are likely to have contributed to the higher water contents in the deeper horizons and lateral flow into the plot.

5.1.4 Sensor-soil contact.

Excellent sensor-soil contacts were observed for all the sensors, except for one tensiometer (T6 at 60cm, Figure 4.1) which had a gap between the sensor tip and the bottom of the installation hole (Plate 11). In contrast Plate 12 shows the typical sensor-soil contact observed for all the remaining sensors. It is thought that air below T6 trapped when the soil slurry was being added.

5.1.5 Roots.

Roots were observed throughout the profile to the depth of the gravels at about 95cm. The pasture cover was severely stressed by the time of the excavation (Plate 11) so an increase in rooting depths was anticipated. Roots were found with some preferential proliferation down the outside of access tubes and tensiometer columns, and around the outside of the resistance sensors.

Plate 11: Poor sensor-soil contact below the tensiometer cup (T6) at 60cm depth.

Plate 12: Excellent sensor-soil contact below the tensiometer cup (T3) at 30cm depth.

5.2 Irrigation and rainfall events.

Rainfall and irrigation events which occurred during the trial are recorded below (Table 5.3).

5.2.1 Rainshelter effectiveness.

Soil drying was greatly increased with the use of the rainshelter. Rainfall over the trial period was much greater than normal, 781mm fell between 22 March 1992 and 31 January 1993; while the mean annual rainfall for Lincoln is 681mm (NZ Met Service, 1986).

Whilst the shelter, when used as planned, effectively kept rainfall off the surface of the field plot, there were some exceptions (Table 3.1). These occurred as a result of unforecast rain, the unintentional removal of the shelter, or occasionally as the result of rain being blown through the windbreak cloth walls during rainfall events. In this latter case any effects are believed to have been small (1mm or less), most was observed to have been intercepted by the pasture cover and limited to the periphery of the plot. It is believed that most of this intercepted rain would have evaporated soon after the rainfall event. No measurements were taken to verify this assumption. The prevailing direction of the wind-blown rain was southerly.

5.2.2 Lateral flow effects.

Associated with the relatively high rainfall, lateral sub-surface movement of soil water into the experimental plot was observed, flowing from the wetter surrounding soil (i.e. higher ψ_t) (see section 5.1.2). The plot buffer of a minimum of 1.3m between the sensors and the edge of the plot was therefore insufficient.

This effect was first observed when taking routine neutron probe measurements (Figure 5.2). Only two of the neutron probe tubes appear to have been affected (Tube 2 was unaffected, see site plan, Figure 4.1). The largest effect is observable at depths > 0.4m.

Table 5.3: Rainfall and irrigation events.

Date	Julian Day	Rainfall (mm)[1]	Comments
31 March	91	(5.5)	Field site is allowed to wet up with both rainfall and irrigation.
1 April	92	5.8 (10.5)	
2 April	93	16 (7.5)	
3 April	94	20.5	
4 April	95	2.8	
6 April	97	(55.3)	
26 April	117	1	Unforecast rainfall.
2 July	184	1.5	Field site allowed to wet up with rainfall.
5 July	187	13.5	
9 July	191	32	
10 July	192	1.5	
25 August	238	4.5	Field site allowed to wet up with rainfall.
26 August	239	50	
27 August	240	16.6	
28 August	241	25.8	
29 August	242	16	
30 August	243	2	
31 August	244	1	
20 October	294	0.5	Rainshelter inadvertently removed.
21 October	295	2.8	
22 October	296	12	
17 November	316	14.6	Rainshelter inadvertently removed.
18 November	317	13	
19 November	318	2.5	
2 December	337	5	Rainshelter inadvertently removed.
3 December	338	5.5	
4 December	339	7.5	
6 December	341	1.5	

[1] brackets denote irrigation.

Soil layer geometry (section 5.1.2) may explain why all the sensor arrays were not affected by lateral flow below approximately 50cm. Finer textured layers which dipped over the coarser, more transmissive layers may have functioned as impermeable boundaries to water flow. Hence, it is suggested that this effect, combined with poor soil hydraulic conductivity due to drying, would have prevented, or at least restricted, lateral water movement across the whole plot.

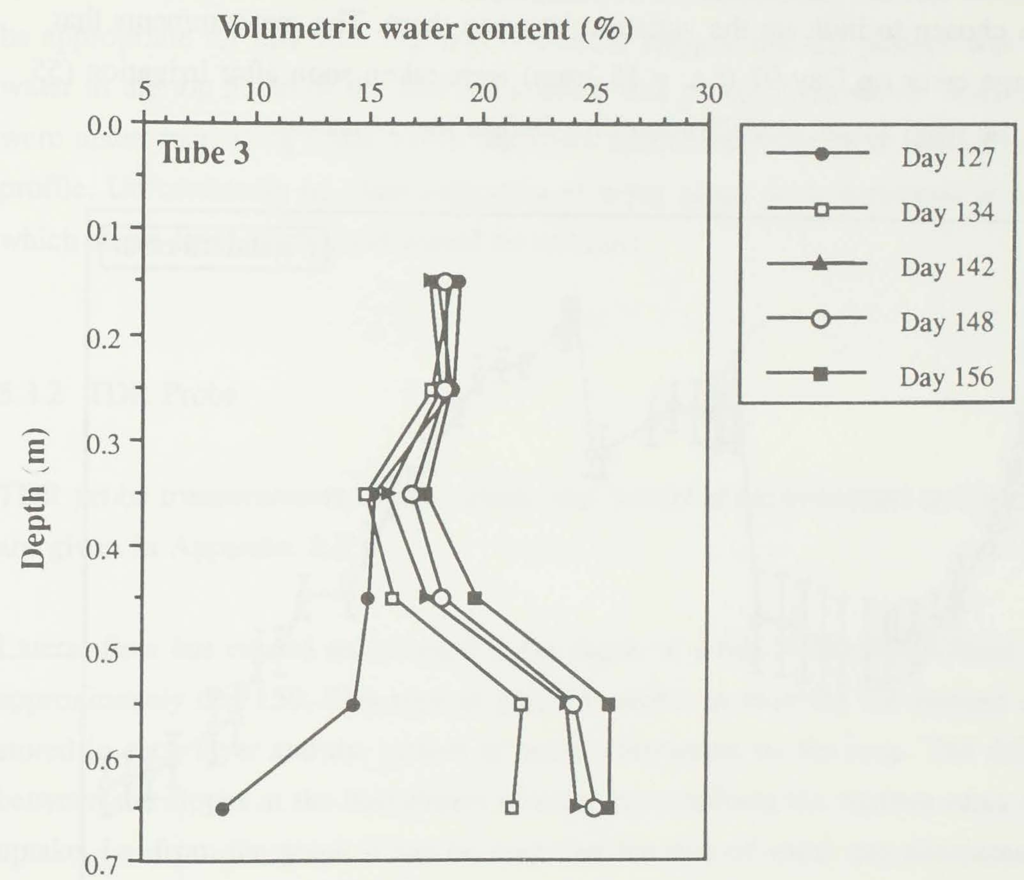


Figure 5.2: **Lateral flow effects for tube 3 shown by successive neutron probe measurements.**

After the trial plot was re-wetted back to field capacity (or full point) on 31 August (julian day 244) the significance of any lateral flow effects was diminished as ψ_t tended towards equilibrium. Because lateral flow has made comparison between the replicates unreliable prior to this, the following analysis is mainly concerned with data obtained after 31 August.

5.3 Sensor results from the field trial.

5.3.1 Neutron probe.

Results for the trial period are summarised in Figure 5.3. (see Appendix 2.1 for all field data). These results are for the 0 to 50cm depth only (the expected effective rooting zone of the pasture, which is discussed below). Standard errors of the mean of the three tubes have been chosen to indicate the variation between them. The measurements that give the very large error on Day 97 (s.e. = 15.3mm) were taken soon after irrigation (55 mm) indicating the need for an equilibration time before measurement.

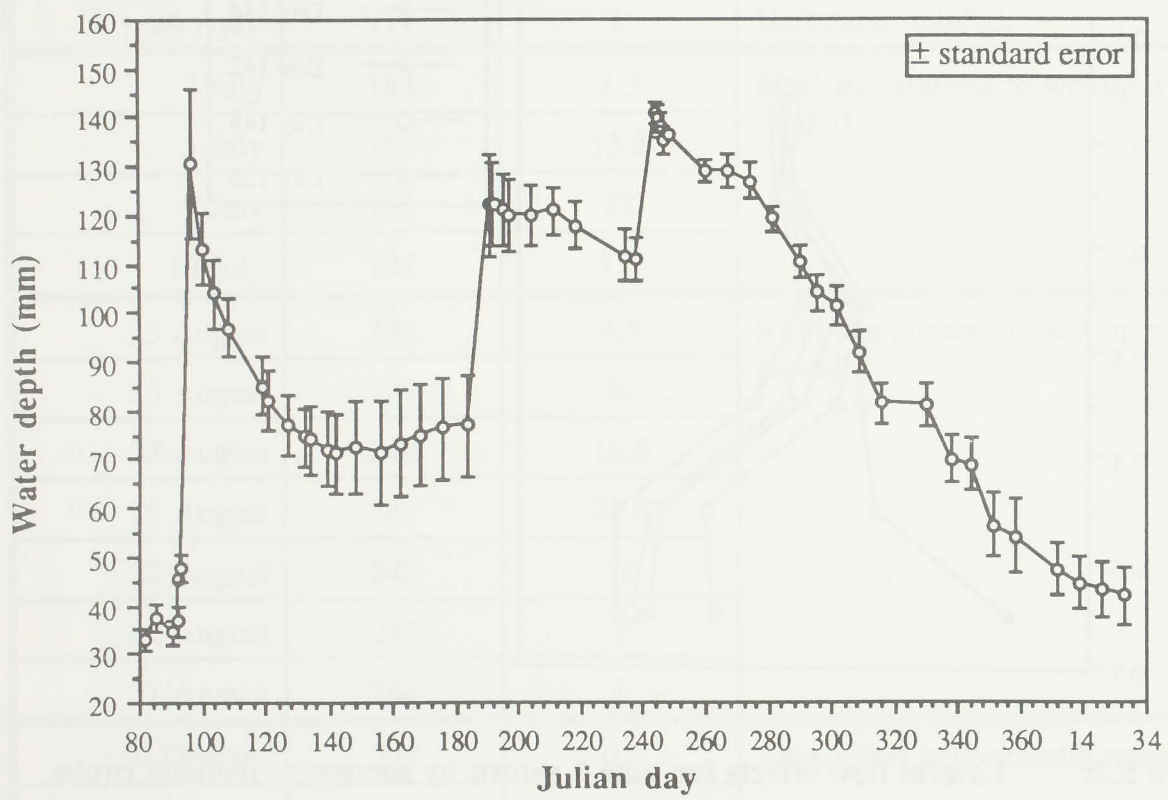


Figure 5.3: Neutron probe measured water content for the 0 to 50cm depth for the trial period.

Lateral flow occurred (section 5.2.2) between days 142 and 191, producing a marked increase in standard errors.

Figures 5.4 a to c show a drying sequence for all three tubes for selected days between days 246 (1992) and 27 (1993). These water content profiles indicate the spatial variability in soil moisture within this small site. This variability increased as the soil dried, especially when the pasture was severely stressed (Figure 5.4c and Figure 5.5).

Measurements for Tubes 1 and 3 show reasonably close agreement with each other over this drying cycle, except when the soil is very dry (Figure 5.4c), when respective θ_v values are between 3 and 6 % different. However the shapes of both water content profiles remain similar. Tube 2 shows good agreement with Tubes 1 and 3 for the top 40cm, but below this the difference is marked for all dates.

The selection of a 50cm effective rooting depth for calculating deficits would seem to be appropriate for this trial. Figures 5.6a and b suggest that the pasture was abstracting water in the top 50cm of the soil when water was plentiful. However when the plants were under increasing water stress, the roots abstracted water from deeper down the profile. Unfortunately no plant indicators of water stress were measured to establish at which stress level plant yield would be affected.

5.3.2 TDR Probe.

TDR probe measurements for the whole trial period are summarised in Figure 5.5. Data are given in Appendix 2.2.

Lateral flow has caused an increase in the depth of water in the 50 to 70cm layer after approximately day 150. This type of graph is useful in showing the amount of water stored in each layer and the pattern of water abstraction by the crop. The difference between the slopes at the boundaries of each layer reflects the relative rates of water uptake, i.e. from the graph it can be seen that the rate of water use decreases with depth when water is readily available to the plant. Water in the 50 to 70cm layer only begins to be taken up by the crop by about Julian Day 302 (approximate deficit of 60mm in the top 50cm). The rate of water loss from this layer after this date is similar to or greater than the rates of the loss from the other.

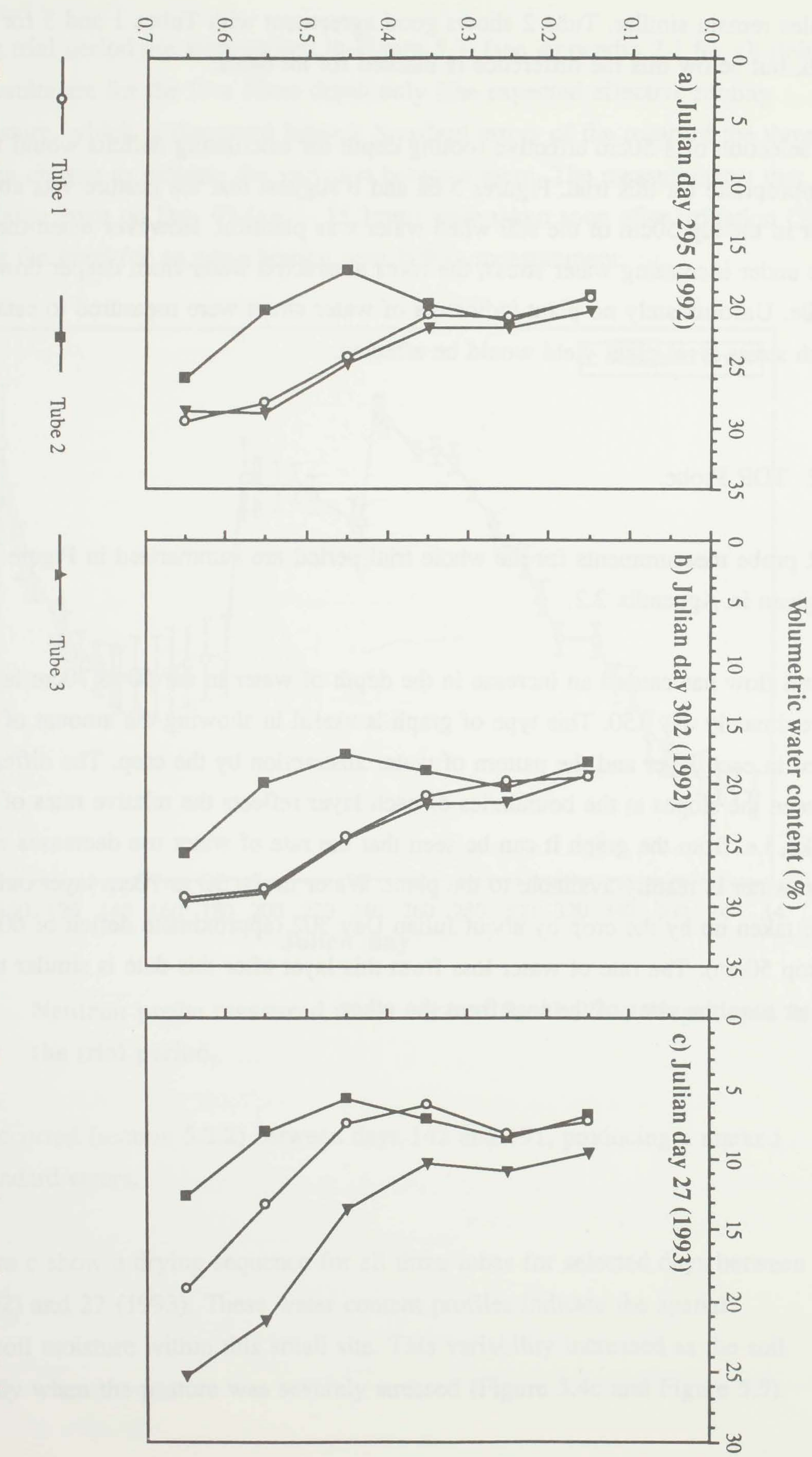


Figure 5.4: Drying sequence for three tubes for three selected dates when soil water content (Θ_v) between 0 and 50cm depth is: a) at full point; b) at possible irrigation trigger point; and c) is causing severe observable plant stress.

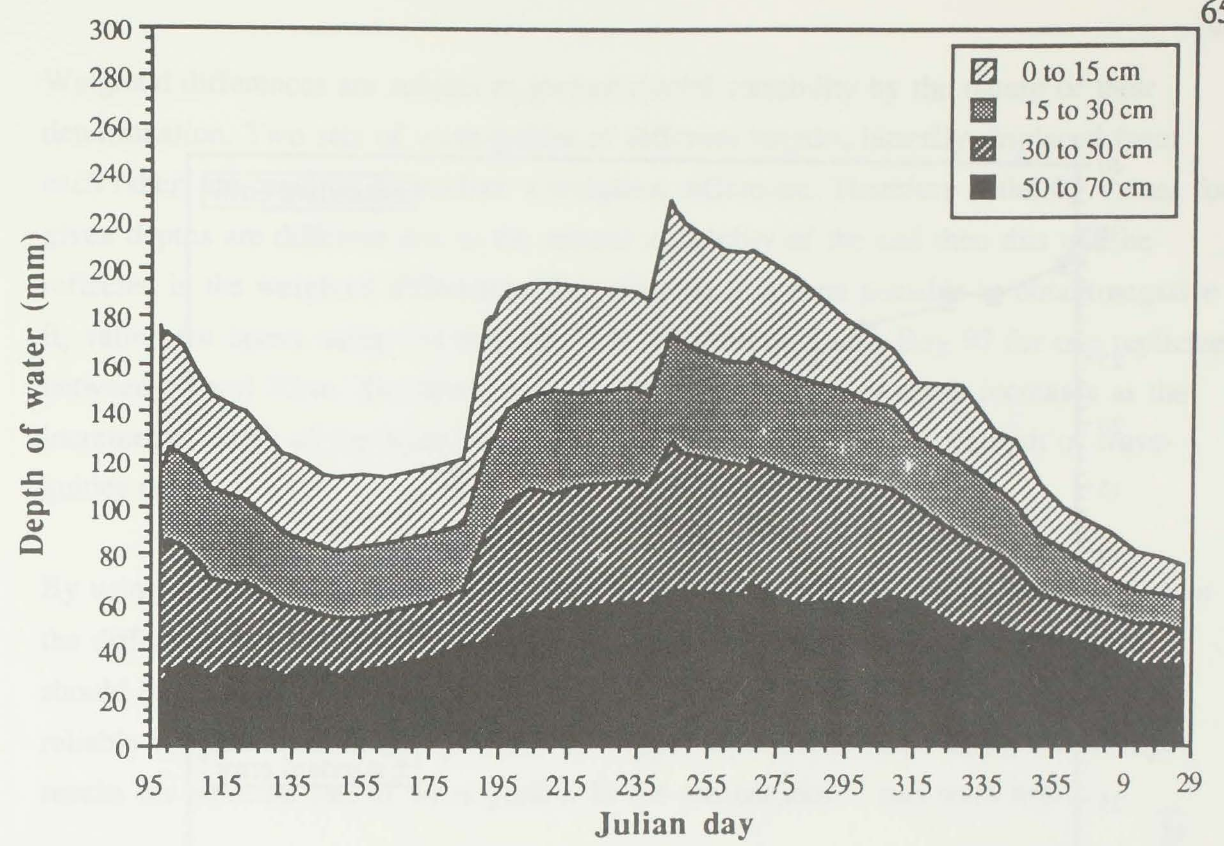


Figure 5.5: TDR measured changes of layer water contents (mm) over the trial period. Results represent the average of 3 sets of replicate rods.

The use of weighted averages.

Unlike the neutron probe the TDR method does not readily discriminate θ_v at different depths, but averages θ_v over the total length of the wave-guides. One method to estimate θ_v for different depth layers is to use weighted averages:

$$\theta_{v1,2} = \frac{\theta_{v2}d_2 - \theta_{v1}d_1}{(d_2 - d_1)} \qquad 5.1$$

where, θ_{v1} and θ_{v2} represent average θ_v for the layers between depths 0 to d_1, and 0 to d_2, respectively. $\theta_{v1,2}$ is the θ_v for the layer between d_1 and d_2.

Weighted differences were used to calculate θ_v (%) for the 30 to 50cm and 50 to 70cm layers in Figure 5.6b and c. Standard errors are used to indicate the variability between the three calculated values. Comparison of the unweighted 0 to 30cm layer (Figure 5.6a) with these layers shows that the use of the weighted difference method accounts for some of this variation.

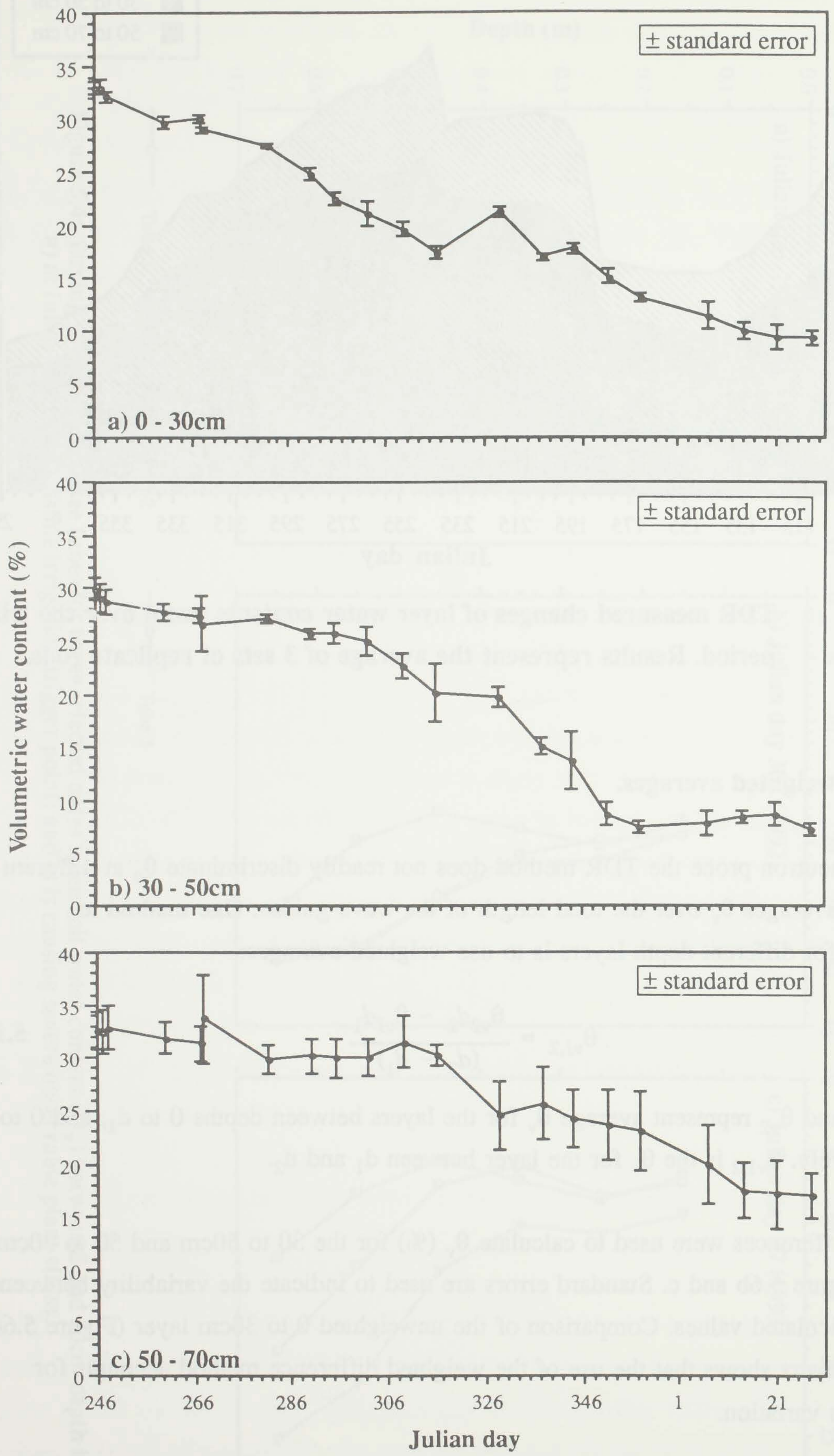


Figure 5.6: TDR volumetric water contents for three layers. Weighted differences were used for the 30 to 50cm and 50 to 70cm layers.

Weighted differences are subject to greater spatial variability by the nature of their determination. Two sets of wave-guides of different lengths, laterally displaced from each other, are required to produce a weighted difference. Therefore if the θ_v values for given depths are different due to the natural variability of the soil then this will be reflected in the weighted differences. For example it is even possible to obtain negative θ_v values for layers using this method. This occurred on Julian Day 97 for one replicate between 50 and 70cm. The likelihood of recording this type of result increases as the incremental depth of the layer in question decreases (decided by the length of wave-guides used).

By using weighted differences averaged across several replicate sets of wave-guides, or the difference between the averages of wave-guides of different lengths, the errors should be reduced. Therefore to overcome problems of spatial variability and obtain reliable weighted difference θ_v values for deeper layers, it is essential to use average results for replicate sets of wave-guides. In the present case 3 sets were used.

5.3.3 Comparison of the neutron probe and TDR results.

Here, data are expressed as the average volumetric water content value for each layer.

Comparison of instrument calibrations.

Figure 5.7 and Table 5.4 show linear regressions between the neutron probe measured θ_v and TDR measured θ_v between Julian Days 246 (1992) and 27 (1993).

Table 5.4: Regressions of neutron probe measured θ_v against TDR measured θ_v.

Layer depth	Intercept	Slope	R^2
0 to 30cm	2.16	0.795	0.92
30 to 50cm	4.12	0.699	0.83
50 to 70cm	3.61	0.769	0.84
0 to 70cm	2.94	0.773	0.89

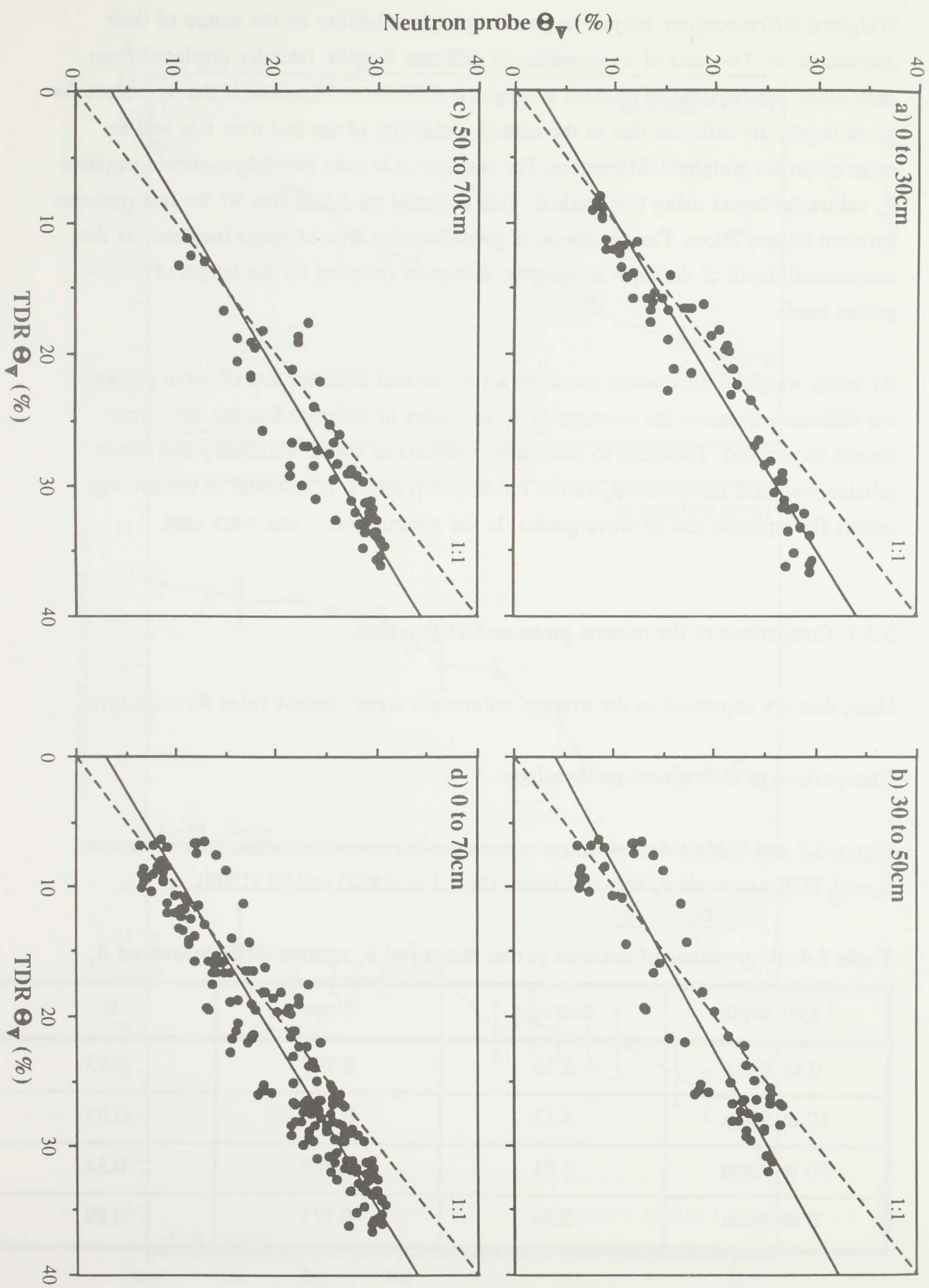


Figure 5.7: Linear regressions between neutron probe and TDR measured volmetric water content (θ_v).

The relatively large deviation of the slopes in Table 5.4 from unity was unexpected. Without a direct measurement of θ_v from gravimetric sampling it is not possible to explain the reason for these differences. One possible reason for the difference is that the neutron probe calibration used may not be appropriate for this Templeton soil.

The Wakanui soil used for the field calibration is of a finer texture and may have greater dry bulk densities in the subsoil, although both soils can be expected to have similar chemical composition. Therefore it is assumed that the slopes of the neutron probe calibrations for the two soils should be similar.

The Trase TDR system uses a built-in calibration similar to Topp *et al.* (1980) (Trase operators manual, p44) which was empirically shown to be suitable for most mineral soils (Topp *et al.*, 1980). A further possibility is that the wave-guide holes are being used as preferential channels for water movement.

In summary the reason for the systematic difference between the neutron probe and TDR measurements is unknown. The strength of the regressions means that it is most unlikely to be due to spatial variation of the soil. Neither calibration is necessarily accurate, but both may contribute to the difference in readings.

The greatest differences between θ_v measured by the two methods occur at the extremes (wet and dry ends). The relative differences are much smaller when comparing readings of between 10 and 20%. This range of moisture is likely to be critical to irrigation scheduling, particularly regarding trigger points.

5.3.4 Tensiometers.

Tensiometer readings for both measurement depths are listed in Appendix 2.3, and are summarised in Figure 5.8. As with the soil water content sensor measurements, there are some relatively large variations in suction readings between replicates at both depths.

Two drying curves (including one complete wetting-drying cycle) were monitored for both depths. At the 30cm depth there is a marked difference in the magnitude of the standard error, used as an indicator of inter-sensor variation, between the two drying curves. When the soil dried over the first cycle, the range of the readings for the three replicates remained relatively small, between 2 and 17.5 kPa (julian days 112 and 132,

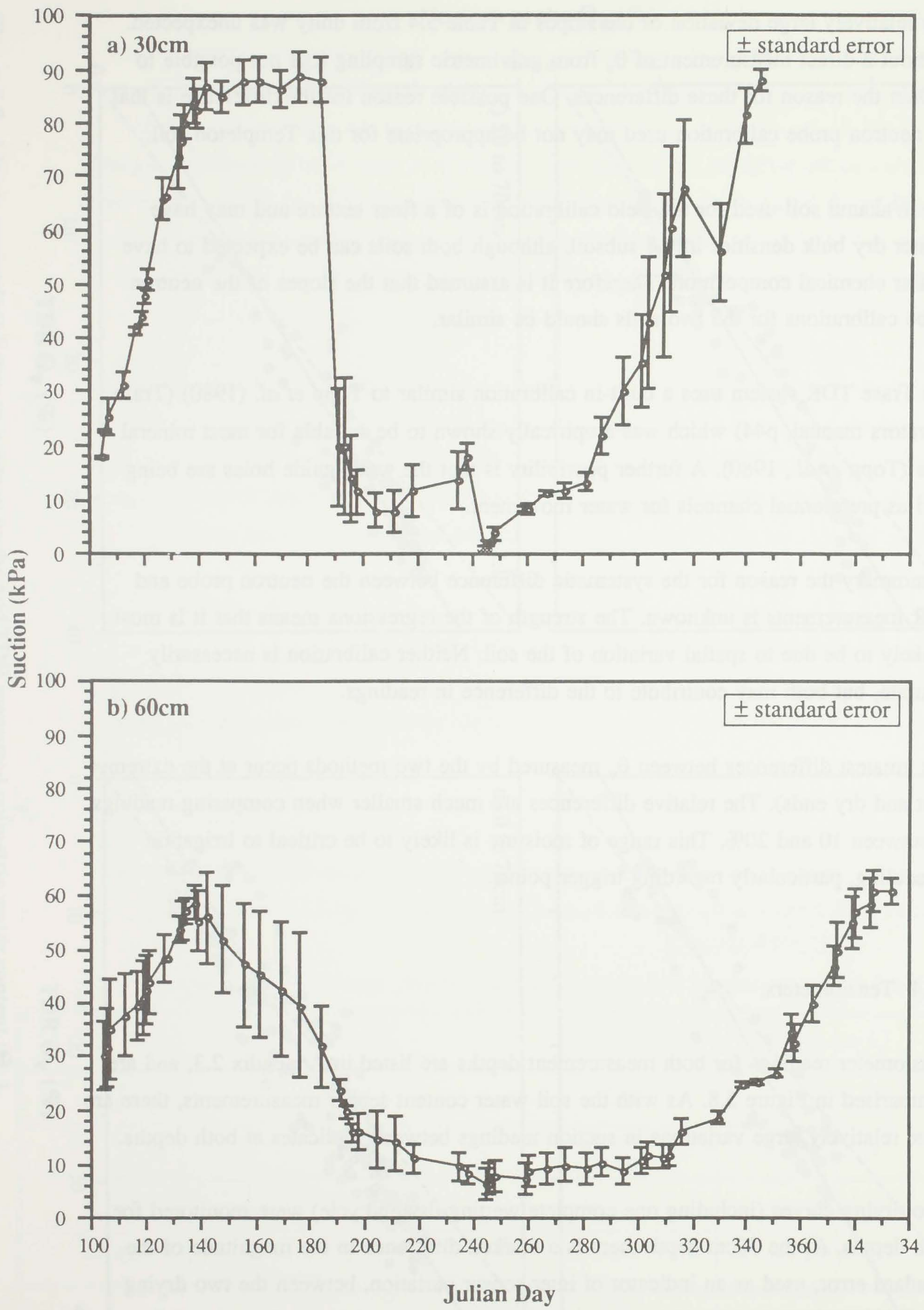


Figure 5.8: Tensiometer measurements of soil water suction at 30cm and 60 cm depths. Each point represents the mean ± standard error for three tensiometers at each depth.

respectively). Measurements for the second drying curve range from 2 to 52 kPa (julian days 259 and 312, respectively).

There are no obvious reasons for this increase in variability between replicates over the two drying curves. It had been hypothesised that the hydraulic contact between the sensor and soil had somehow been degraded after the first drying-wetting cycle, and this effect may have been increased by slight movement of the tensiometer column during purging operations. Poor contact between the soil and cup could result in tensiometer readings lower than the suction of the soil surrounding the cup. This is now thought to be unlikely since evidence from the excavation of the field plot suggests that all the tensiometers at 30cm had excellent sensor-soil contacts. Alternatively there may have been preferential, localised water uptake by the pasture around the tensiometers; or possibly instrument failures (either gauge or cup). There was no reason to believe that problems developed with the gauges for the 30cm tensiometers whilst maintaining (purging) them.

The large variations between the three tensiometer replicates at 60cm on the first drying curve are partly due to incomplete wetting of the soil profile, hence the suction at 60cm is greater than at 30cm, between julian days 102 to 112. Another source of variation may be slow equilibration between the soil surrounding the tensiometer cup after installation. Poor contact below the tensiometer cup of T6 (Plate 11) appears to have little effect on the suction readings. Good contact existed between the soil and cup above the tip.

This may be explained by the equilibration of the vapour pressure of the ambient air in the space below the tensiometer cup with the soil water pressure of the surrounding soil; the relative humidity in the air space is a function of ψ_m. Since there were only small temperature fluctuations at 60cm measured by the thermistor sensor there is assumed to been negligible variation in the vapour and liquid pressures which might have affected the relative humidity and hence suction readings.

Two of the replicates were influenced by lateral flow from outside the shelter-covered area following rainfall. This is shown by an increase in standard errors of the mean after julian 138, as *s* decreases. Complete wetting of the profile had occurred by julian day 246. For both depths, the rate of water uptake is indicated by the slopes of the curves with root uptake occurring from 60cm after approximately julian day 295.

5.3.4.1 Tensiometer measurement range.

Relatively large variations in the upper suction limits of the tensiometers were recorded (Table 5.5).

Table 5.5 The upper limits of suction recorded by the 6 tensiometers in the field.

Depth	Suction (kPa)		
	Tensiometer 1	Tensiometer 2	Tensiometer 3
30cm	80 (148)[1]	92 (142)	90 (142)
60cm	67 (162)	67 (20)	62 (27)

[1] julian days on which these suctions were recorded are shown in brackets.

If the drying stages had been allowed to continue, it is expected that higher suctions would have been measured for the 60cm tensiometers, similar to the 30cm tensiometers. Alternatively these are the highest *s* that may have been achieved for this soil and crop cover, at this depth, and this type of tensiometer. Very slow increases in suction were observed from these tensiometers between 60 and 67 kPa. Purging was required very frequently (every day), in contrast to the tensiometers at 30cm depth which tended to require less frequent purging at these suctions under similar potential evapotranspiration conditions.

5.3.4.2 Maintenance requirements.

No exact quantification of tensiometer maintenance requirement was made. Purging operations when required, were noted. As expected the maintenance requirements changed throughout the trial period. During the cooler months of low PET (PET values below approximately 1-2mm day^{-1}) only infrequent maintenance (once every 3 or 4 weeks) was required below approximately 50 kPa. For higher suctions, tensiometers needed purging about once a week.

Air release from the water column occurred more rapidly during periods of higher PET requiring more frequent purging, and at lower gauge readings than experienced under cooler conditions. Approaching the highest recorded suctions at both depths (from 60 to 65 kPa upwards for the 30cm tensiometers, and 50 kPa upwards for the 60cm ones) tensiometers needed to be purged every two days, if not daily, when evaporative demand was greatest, e.g. between day 300 and the end of the trial. The maximum PET during this period was 6.6mm on day 350 (using data from Lincoln Meteorological Station). Ideally the tensiometers should be purged at least several hours before reading. This was done only when released air was observed to occupy half or more of the volume of the air gap above the gauge, otherwise readings were made before purging. These are important limitations to note if tensiometers are to be used reliably in summer conditions, i.e. with high soil temperature (favouring air outgassing from solution), coupled with high PET rates (causing rapid changes in soil suction).

5.3.5 Data-logged results: sensor resistance and soil temperature.

For the major part of the field trial the temperature and resistance sensors, and the datalogger and multiplexer, proved to be very reliable. Only three problems were encountered:

(1) Loss of data between julian days 244 (0800) and 246 (1200) due to the incorrect down-loading of the datalogger program.

(2) Loss of data between julian days 338 (0400) and 344 (2000) due to the unexpected re-setting of the datalogger due to power failure of the portable computer whilst up-loading data.

(3) Between julian days 357 (1992) and 6 (1993), one of the three thermistors at 15cm depth began to read higher temperatures than the other two (temperatures greater by 6.3°C on day 357). It is speculated that moisture may have entered the sensor, or sensor-datalogger contact giving spurious readings. There had been 23mm of rainfall over the preceding 5 days. It is possible that moisture may have entered through the lead ports through the walls of the "environmentally sealed" box housing the datalogger and condensed on the sensor-datalogger contacts. If this was the case, then the effect was apparently limited to only one sensor.

5.3.6 Watermark sensors.

5.3.6.1 Temperature "corrections".

Sensor resistance is dependent on soil temperature as well as ψ_m. For correction (or more precisely adjustment) the Watermark meter has a built in temperature adjustment knob. By contrast the logger reads unadjusted resistance. Therefore to properly relate logged resistance to meter reading, the former needs to be adjusted by using the same temperature correction (or temperature coefficient) built into the Watermark meter. These temperature-corrected resistances could then be calibrated against meter-read suctions. The steps for this procedure are explained below.

Step 1 - Resistance corrected to a reference temperature.

The suction-temperature correction built into the hand-held meter was first determined by connecting a 13 kOhm resistor across the meter leads. Then the temperature correction knob was set at 8 temperature positions, and the suctions values read from the display. See Table 3.4. This procedure was repeated 6 times over the full temperature range of the meter (12.8 to 32°C).

Table 5.6: Hand-held meter suction-temperature relationship (obtained with a fixed 13 kOhm resistor in place of a Watermark sensor).

Temp. °C	12.8	16	18.3	21	23.9	27	29.4	32
Mean *s* (kPa)	67	75.5	84	90.8	97	102.3	106.3	110.5
Standard deviation	0	0.5	0	0.4	0	0.5	0.5	0.5

The data in Table 5.6 were plotted and a regression line fitted (Figure 5.9). To correct the field resistance data to a reference temperature, only part of this curve was used, approximately between 12.8 and 21°C. This range was chosen because the minimum temperature the meter can adjust for is 12.8°C and the highest field temperatures recorded were approximately 21°C. Between these temperatures the relationship is approximately linear (see Figure 5.10). Therefore, within this temperature range suction changes by 2.95 kPa°C^{-1}. To estimate the **relative** change in resistance with temperature

over the same range, the slope (2.95 kPa) was divided by the mean suction (79.33 kPa), giving a temperature coefficient (β) of 0.0372°C^{-1} (i.e. 3.72%°C^{-1}). This coefficient was used in Equation 3.7. (section 3.4.3) and applied to the logged resistance data. A reference temperature of 17°C (approximately the middle of the selected temperature range) was used, and all logged resistance values were adjusted to this reference.

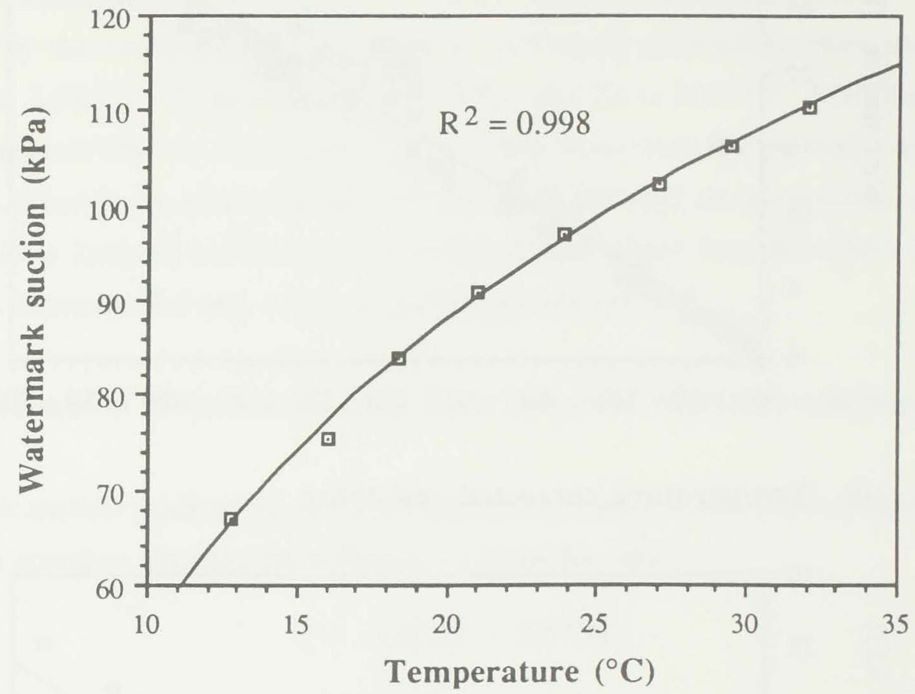


Figure 5.9: The relationship between Watermark meter suction and temperature (as set on the temperature adjustment knob). Results were obtained with a fixed (13 kΩ) resistor across the meter leads.

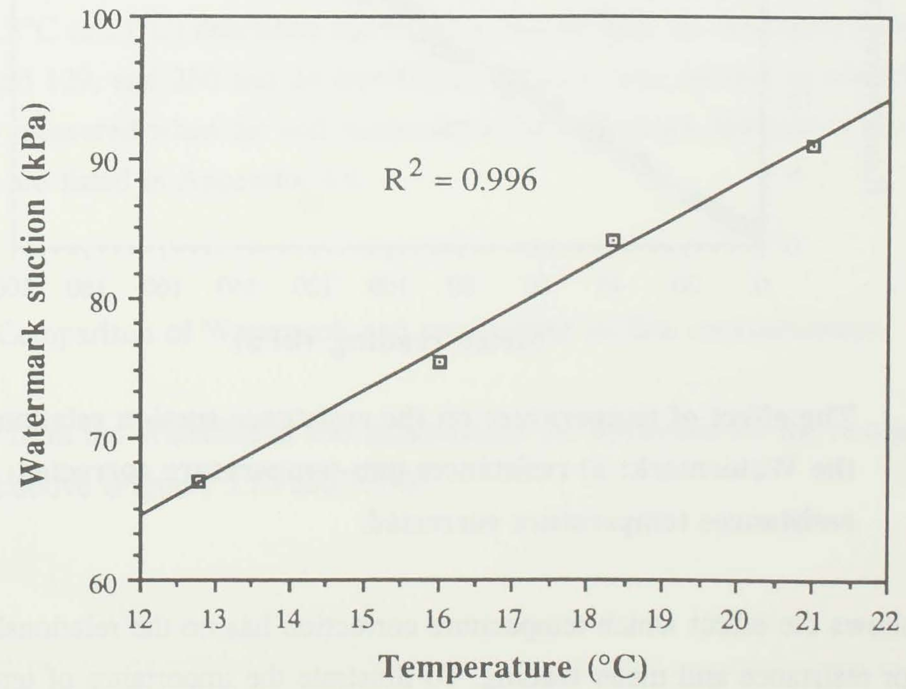


Figure 5.10: Watermark meter suction (kPa) and temperature between 12.8°C and 21°C. (i.e. as Figure 5.9., but with only the lowest 4 point plotted).

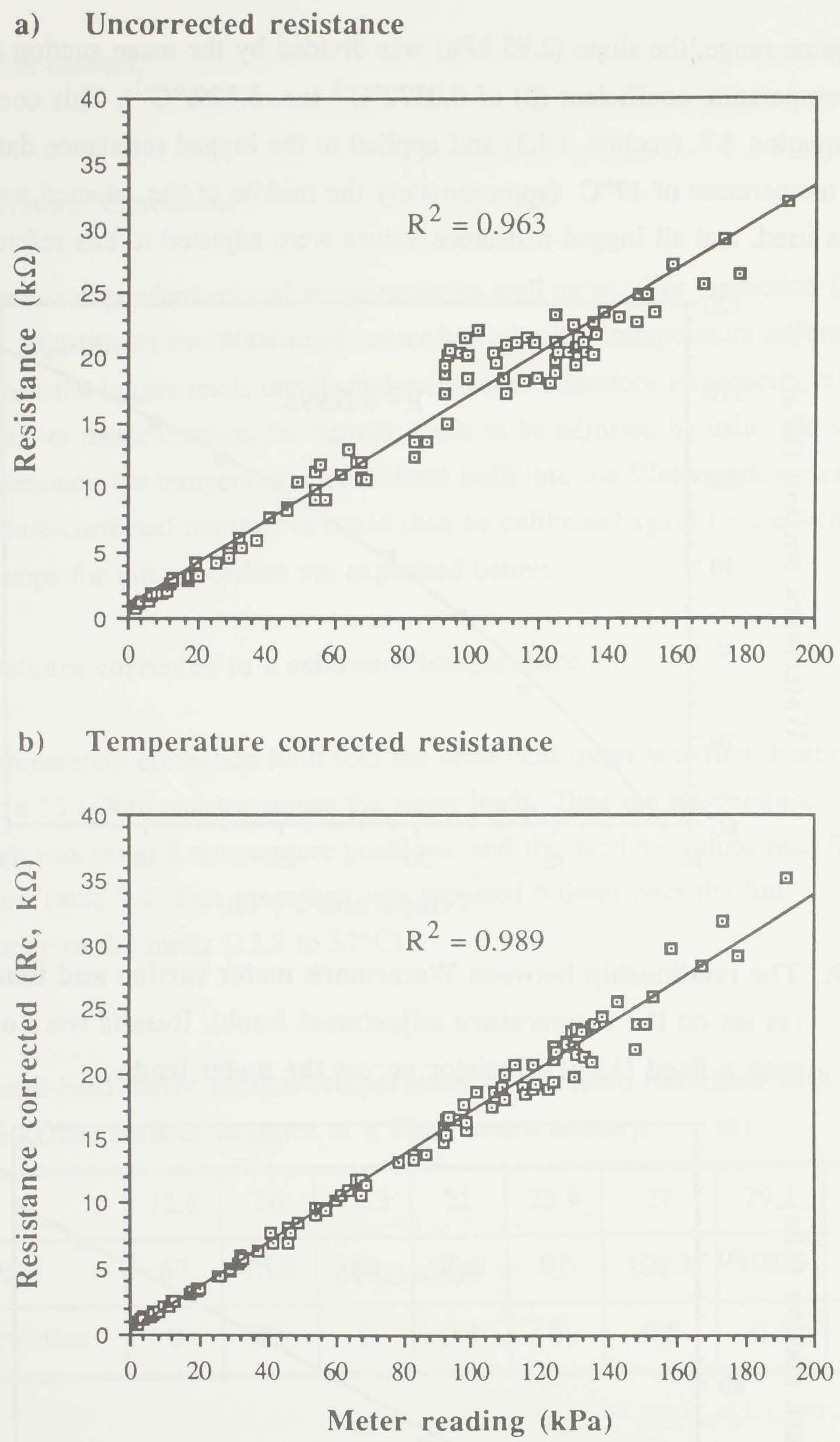


Figure 5.11: The effect of temperature on the resistance-suction relationship for the Watermark: a) resistances non-temperature corrected; and b) resistances temperature corrected.

Figure 5.11. shows the effect which temperature correction has on the relationship between sensor resistance and meter reading. To illustrate the importance of temperature correction, consider Figure 5.11. at a sensor resistance of 20 kOhm. In Figure 5.11(a), a

resistance of 20 kOhm gives meter readings of between approximately 92 and 130 kPa. Whilst temperature corrected resistance of 20 kOhm for the same data gives meter readings of between 110 and 130 kPa. The spread of suction data is approximately greatest at this resistance.

The above temperature coefficient of 3.72%°C^{-1} is about twice the figure of 1.8%°C^{-1} published by the manufacturer. Temperature coefficients reported by other workers range from 2.4%°C^{-1} (Spaans and Baker, 1992), and 2.8 to 3.3%°C^{-1} (McCann *et al.*, 1992). It appears that the manufacturer uses a non-linear temperature correction, not a linear one. Changes in sensor design may also have affected the temperature coefficient. For most New Zealand conditions the coefficient determined from the above linear regression between 12.8 and 21°C should be appropriate.

Step 2 Estimation of suction readings from corrected resistance readings.

Watermark suction readings (s) are estimated from corrected resistance readings by the regression equation obtained from Figure 5.11b in the form:

$$s = -0.5537 + 5.8796R_c \qquad 5.2$$

5.3.6.2. Watermark suction measurements.

Because the soil temperatures for only part of the trial period fell within the temperature range (12.8°C to 21°C) described above, only two periods are analyzed, between julian days 98 and 129, and 280 and 26 (see Figure 5.12). It was decided to use only resistance measured when the soil temperature for each depth fell within this range. The field data are listed in Appendix 2.4.

5.3.6.3. Comparison of Watermark and tensiometer suction measurements.

Readings from the Watermarks and tensiometers are compared for the two periods described above (Figures 5.13 and 5.14).

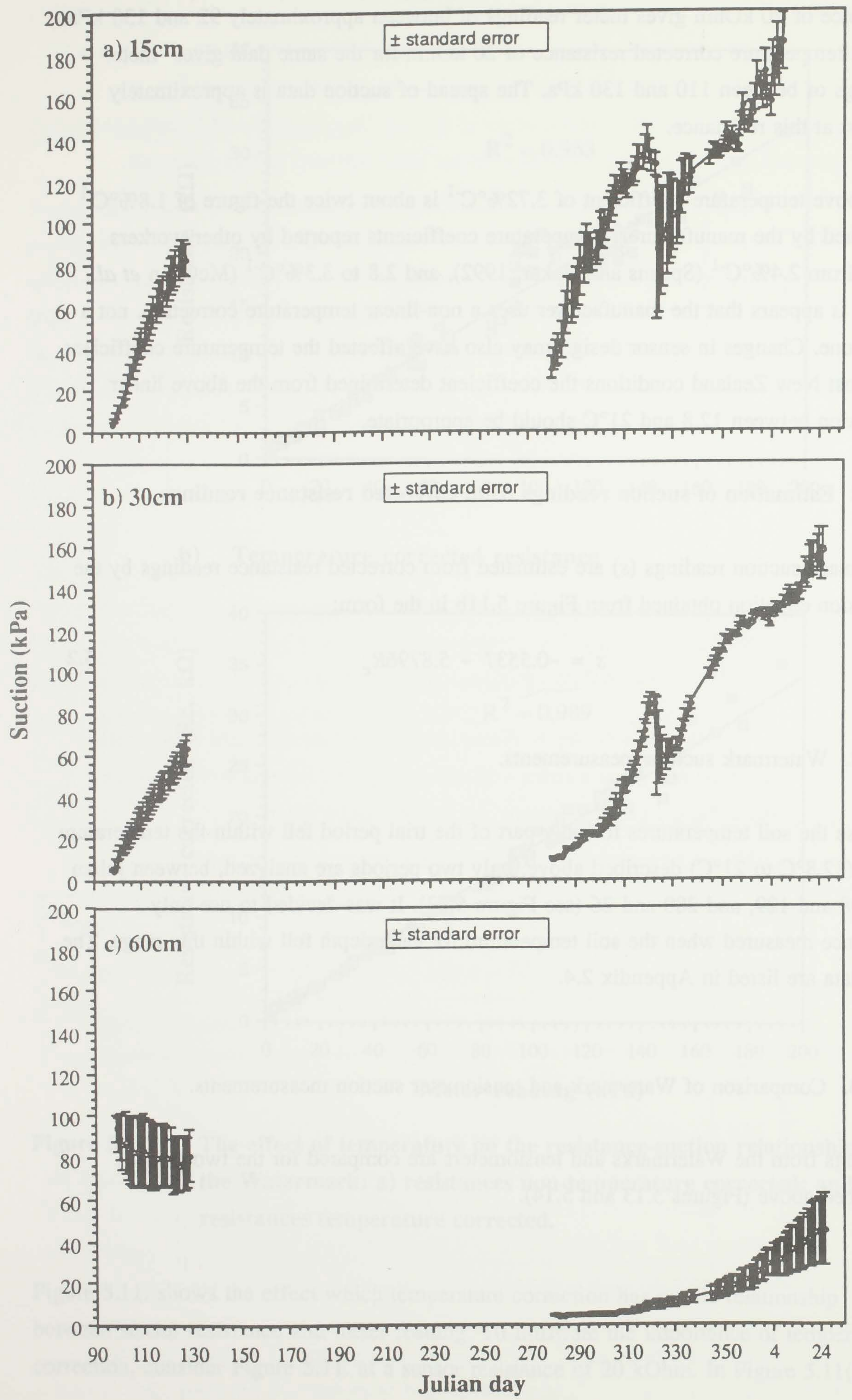


Figure 5.12: Watermark suction (kPa) measurements over two periods.

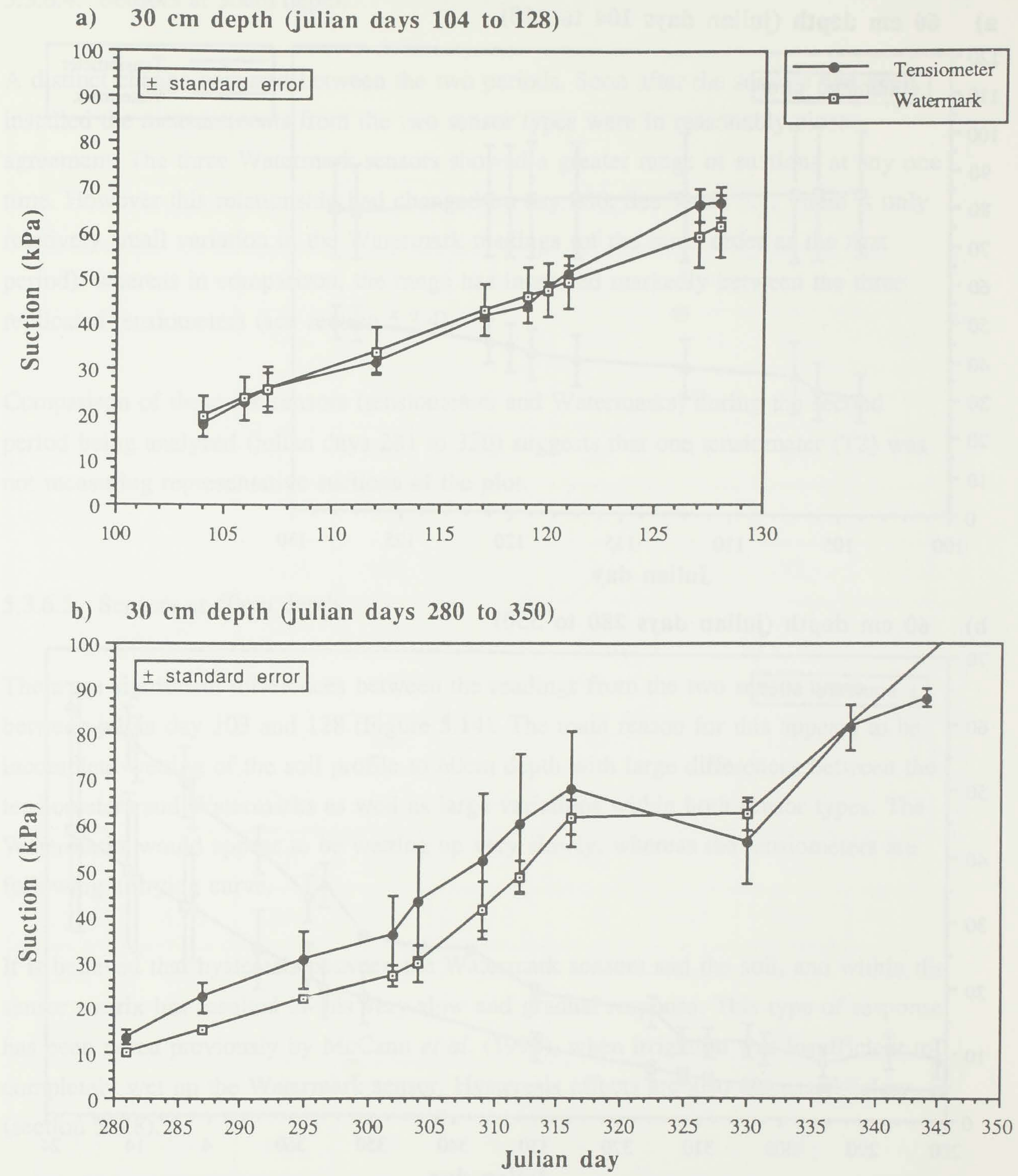


Figure 5.13: Comparison of soil drying curves measured by Watermarks and tensiometers at 30cm depth.

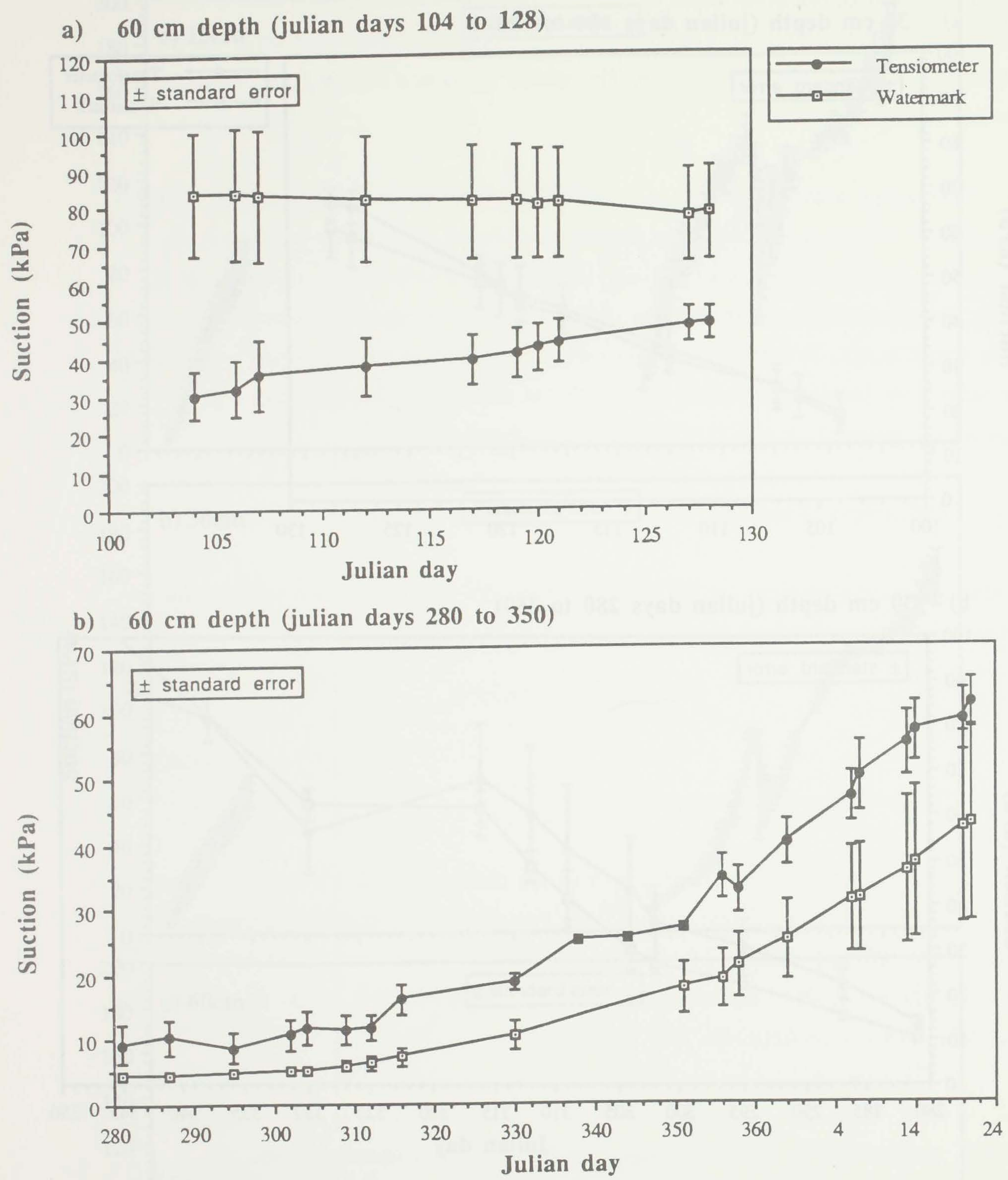


Figure 5.14: **Comparison of drying curves as measured by Watermarks and tensiometers at 60cm depth.**

5.3.6.4. Sensors at 30cm depth.

A distinct change occurred between the two periods. Soon after the sensors had been installed the measurements from the two sensor types were in reasonably close agreement. The three Watermark sensors showed a greater range of suctions at any one time. However this relationship had changed by day 280. See Table 5.7. There is only relatively small variation in the Watermark readings (of the same order as the first period), whereas in comparison, the range has increased markedly between the three replicated tensiometers (see section 5.3.4).

Comparison of these six sensors (tensiometers and Watermarks) during the second period being analyzed (julian days 281 to 330) suggests that one tensiometer (T2) was not measuring representative suctions of the plot.

5.3.6.5. Sensors at 60cm depth.

There are significant differences between the readings from the two sensor types between julian day 103 and 128 (Figure 5.14). The main reason for this appears to be incomplete wetting of the soil profile to 60cm depth with large differences between the tensiometers and Watermarks as well as large variations within both sensor types. The Watermarks would appear to be wetting up very slowly, whereas the tensiometers are following a drying curve.

It is believed that hysteresis between the Watermark sensors and the soil, and within the sensor matrix has resulted in this very slow and gradual response. This type of response has been noted previously by McCann *et al.* (1992), when irrigation was insufficient to completely wet up the Watermark sensor. Hysteresis effects are also discussed below (section 5.3.8).

Large differences were observed between the suction measurements of the two sensor types after the profile had been completely wetted-up (Table 5.8 and Figure 5.14b).

Table 5.7: Comparison of means ± s.e. of suction measured by Watermarks and tensiometers at 30cm depth.

Julian date	Tensiometer (kPa)				Watermark (kPa)			
	Mean	Min	Max	s.e.	Mean	Min	Max.	s.e.
104	17.8	17.5	18	0.2	19.6	12.4	27.6	4.4
106	22.8	18.5	30	3.6	23.5	15.8	32.5	4.9
107	25.3	22	30	3.6	25.4	17.6	34.8	5
112	31.3	30	32	2.4	33.9	25.9	43.9	5.3
117	41.3	40	42	0.7	43	34.4	53.5	5.6
119	43.8	42	46	1.2	46	36.9	57.6	6.1
120	47.7	45	50	1.5	47.1	38.3	58.3	5.9
121	50.8	48	54.5	1.9	49.1	40.3	60.3	5.9
127	65.8	60.5	73	3.7	59.3	49.5	72.4	6.8
128	66.5	62.5	73	3.3	61.3	51.8	74.3	6.7
281	13.3	10	16	1.8	10	9.7	10.5	0.3
287	22	16	28	3.5	14.9	14.5	15.1	0.2
295	30.3	20	42	6.4	21.8	19.8	23.2	1
302	35.8	23	52.5	8.7	26.7	22.9	30.6	2.2
304	43	26	67	12.3	29.4	25.5	33.3	3.9
309	51.8	32	81.5	15.1	41.1	34.7	47.6	6.5
312	60.3	38	90	15.5	48.6	42	53.2	3.4
316	67.8	49	92	12.7	61.8	54.4	66	3.7
330	56	46	74	9	62.5	55.9	69	3.8

Table 5.8: Comparison of means ± s.e. of suction measured by Watermarks and tensiometers at 60cm depth.

Julian day	Tensiometer				Watermark			
	Mean	Min.	Max.	s.e.	Mean	Min.	Max.	s.e.
281[1]	9.3	4	14	2.9	4.4	4.1	4.8	0.2
287	10.3	5	14	2.7	4.5	4	4.9	0.3
295	8.7	4	12	2.4	4.8	4	5.4	0.4
302	10.7	6	14	2.4	5	4	5.8	0.5
304	11.7	7	16	2.6	5.2	4.1	6	0.6
309	11.3	7	15	2.3	5.8	4.3	7.1	0.8
312	11.7	8	14	1.9	6.2	4.4	7.9	1
316	16	12	20	2.3	7.2	4.9	9.7	1.4
330	18.7	16	20	1.3	10.4	6.9	14.5	2.2
351	27	26	28	0.6	17.7	11.1	24.7	3.9
356	34.7	28	38	3.3	19	11.6	27.1	4.5
358	32.7	26	38	3.5	21.1	12.7	30.2	5.1
364	40	34	46	3.5	25	15.6	35.9	5.9
6[2]	47	41	54	3.8	31.2	18.6	45.8	7.9
7	50	40	58	5.3	31.4	18.2	46.8	8.3
13	55	46	63	4.9	35.6	18	56.5	11.2
14	57	48	63	4.6	36.8	18.3	58	11.5
20	58.7	50	66	4.7	42.1	21	69.9	14.5
21	61	54	67	3.8	42.9	21	71.4	14.9

[1] 1992; [2] 1993.

It is thought that soil heterogeneity, particularly the layering effects observed in the BC horizon below approximately 50cm (Figures 5.1 to 5.3), has had considerable influence upon the transmission and storage of water within this small area (see section 5.1) and upon the inter-sensor variability. Unfortunately it is not possible to quantify this.

There is also doubt as to the accuracy of the zero-setting of these tensiometers and gauges in this trial, because of the relatively large variation in tensiometer readings at the lower suctions (Table 5.8, e.g. julian day 281). This results in an apparent offset of 6 kPa between the tensiometers and Watermark sensors (using the mean readings from the two sensor types at 60cm) of 6 kPa (Figure 5.14) after the profile was wetted up.

Each of these gauges for the 60cm length tensiometers have zero-setting screws which should allow the gauge to read the soil suction at the tensiometer cup without having to take into account the length of water-column, i.e. the correction for the head of water above the cup (which for a 60cm length would be 6 kPa). Before installing the tensiometers in the field all the tensiometers were zero-set, with the tensiometer cup fully immersed in water.

After the tensiometers (at 60cm depth) were removed from the soil they were again immersed in water to check their zero-setting Two tensiometers had developed an offset of +5 kPa (T1 and T3) whilst the remainder had a negative offset (the amount is unknown as the gauge has a stop to prevent the needle moving below zero). This may help explain some of the variation and difference between the two types of sensor. No attempt has been made to adjust the data since it is unclear why, or when, the offset had developed.

It is possible that one, or more, of these tensiometers were not accurately zeroed before installation, despite the gauges reading zero suction (perhaps due to friction in the gauge zeroing mechanism). The difficulty in establishing whether a gauge is accurately set is a factor that should be considered when using these sensors.

From the field measurements it would appear that the gauge tensiometers when properly zeroed, and when the effect of soil heterogeneity is removed, are more precise instruments to use than the Watermark sensors. This may be expected since the tensiometers are directly measuring soil suction. However, they require much greater maintenance and may be more prone to damage or wear (especially the gauge). The use of replicated Watermark sensors improves the measurement precision and reduces the influence of spatial variability.

5.3.7 Gypsum blocks.

Field data are listed in Appendix 2.5.

5.3.7.1 Temperature correction.

Like the Watermark sensors, gypsum block resistance should be corrected to a reference temperature. However, unlike the Watermark meter the gypsum block meter had no temperature adjustment control and hence no correction circuit. Since meter readings were not temperature referenced, field data were used to estimate the temperature coefficient.

For the 3 blocks at 30cm, the logarithm of resistance, as measured by the datalogger in the field, was plotted against temperature, between julian days 240 and 290 (Figure 5.15). Data for this period were chosen because suction values were low (Figure 5.8). It was assumed that there would be little or no response to changes in suction by the blocks, whilst the calcium sulphate solution in the block remained at saturation. Therefore any change in resistance was a consequence of temperature change. Gypsum blocks at 30cm were also preferred because they produced the greatest amount of data with a range of temperatures (between approximately 5 and 11.5°C) over this period.

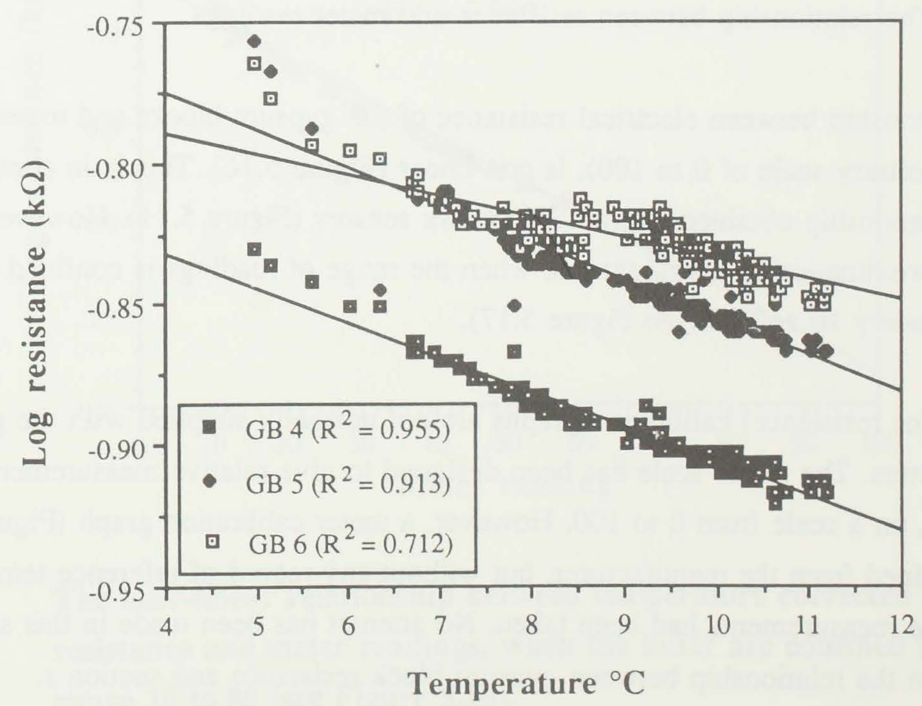


Figure 5.15: **The relationship between log resistance (kΩ) and temperature for 3 gypsum blocks at 30cm depth between julian days 240 and 290.**

Unfortunately these assumptions do not appear to be valid for one of the blocks (GB6) because there is a break in the curve (Figure 5.15). One possible explanation for this is that water may have been preferentially removed from the soil adjacent to the block causing an increase in soil suction around the block.

The regressions for the other two curves indicate a strong log-linear resistance-temperature relationship. The slopes (and temperature coefficients) for blocks GB4 and GB5 are 1.23%°C^{-1} and 1.33%°C^{-1}, respectively. The average of these two coefficients (1.28%°C^{-1}) was used to correct the resistance readings from all blocks. This average coefficient value agrees reasonably well with one determined by Wellings *et al.* (1986) who used a coefficient of 1.23%°C^{-1} for their blocks. Equation 3.7 (section 3.4.3) is used to correct the resistance to a reference temperature of 17°C.

The temperature range in Figure 5.16 shows that lower temperatures than would normally be experienced for irrigated soils in New Zealand, were used to estimate the temperature coefficient. This is in contrast to the range (12.8 to 21°C) used to determine the Watermark sensors (see section 5.3.6.1). However by using log-linear resistance and temperature data, it is expected that a reasonable resistance correction can be made. Data presented by Wellings *et al.* (1986) supports this.

5.3.7.2 The relationship between resistance and meter readings.

The relationship between electrical resistance of the gypsum blocks and meter readings (on an arbitrary scale of 0 to 100), is non-linear (Figure 5.16). This is in contrast to the linear relationship obtained for the Watermark sensors (Figure 5.11). However there is a close approximation to a straight line when the range of readings is confined to between approximately 10 and 80 (see Figure 5.17).

Suction (or resistance) calibration graphs are not normally supplied with the gypsum block meters. The meter scale has been designed to give relative measurements of soil moisture, on a scale from 0 to 100. However, a meter calibration graph (Figure 5.18) was obtained from the manufacturer, but without any record of reference temperature at which the measurements had been taken. No attempt has been made in this study to determine the relationship between gypsum block resistance and suction *s*.

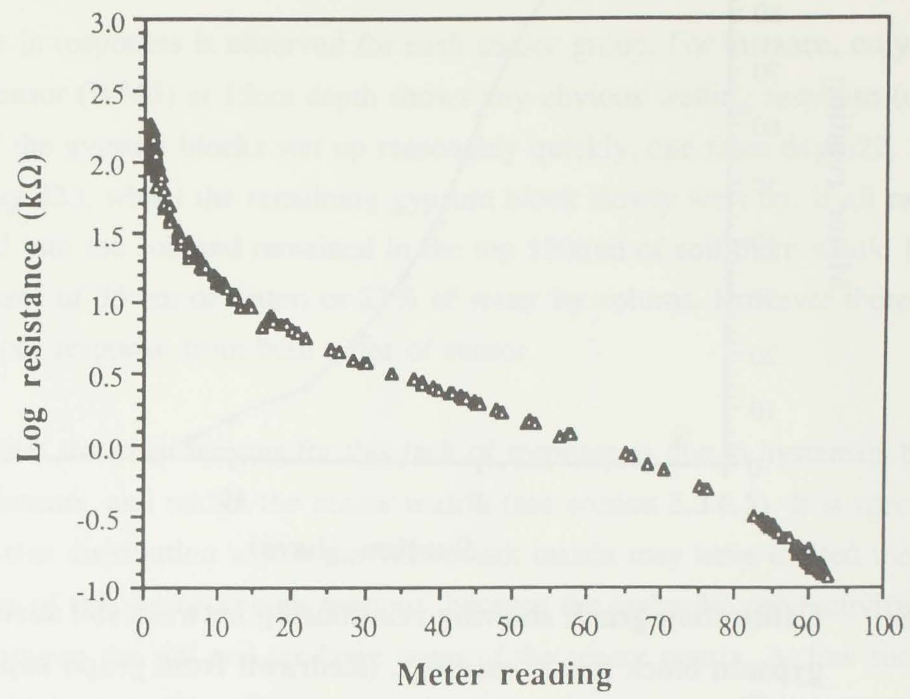


Figure 5.16: The relationship between temperature corrected resistance and gypsum block meter readings.

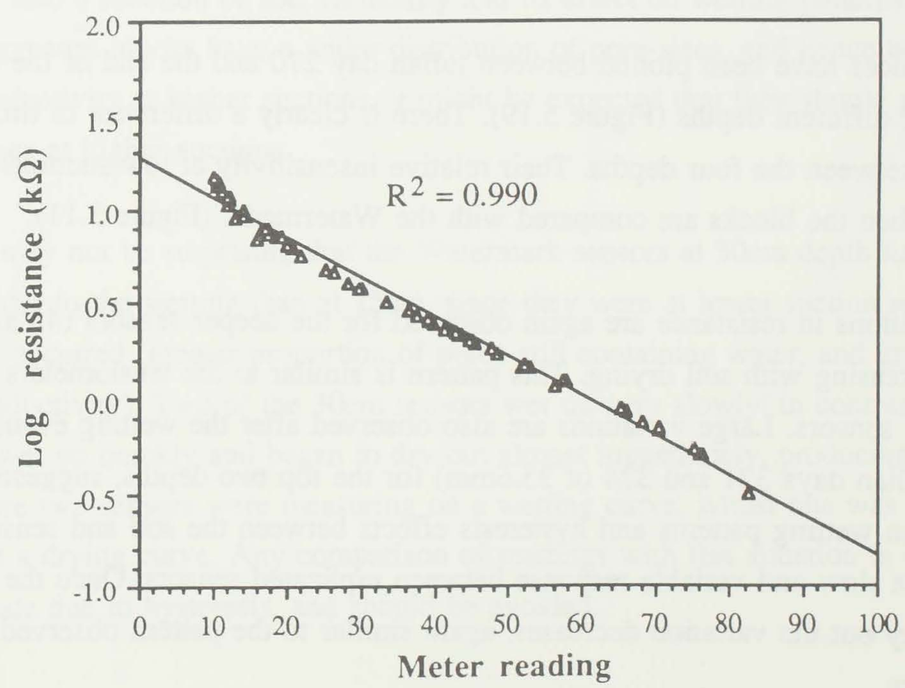


Figure 5.17: The near-linear relationship between temperature corrected resistance and meter readings, when the latter are confined to the range 10 to 80 (see Figure 5.16).

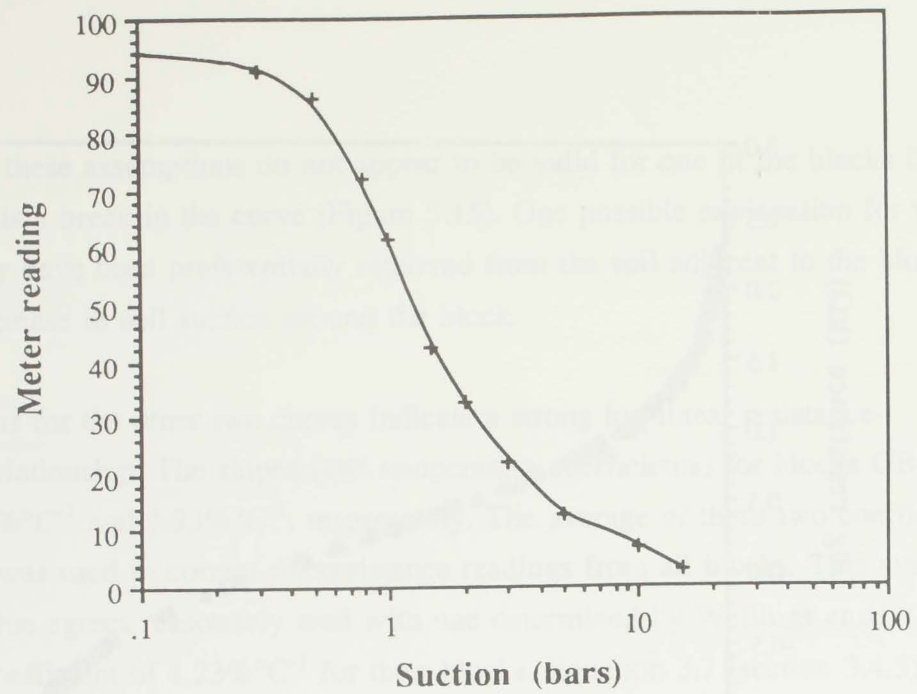


Figure 5.18: **Calibration graph showing relationship between soil suction and gypsum block meter readings. (Redrawn from graph supplied by block manufacturer, Electronics Unlimited, Sacramento, Calif.)**

5.3.7.3 Gypsum block resistance readings.

Log resistances have been plotted between julian day 270 and the end of the field trial for the four different depths (Figure 5.19). There is clearly a difference in time-responses between the four depths. Their relative insensitivity at low suctions is apparent when the blocks are compared with the Watermarks (Figure 5.11).

Large variations in resistance are again observed for the deeper sensors (45 and 60cm), greatly increasing with soil drying. This pattern is similar to the tensiometers and Watermark sensors. Large variations are also observed after the wetting event (rainfall between julian days 321 and 324 of 35.6mm) for the top two depths, suggesting variations in wetting patterns and hysteresis effects between the soil and sensor, producing a slow and variable response between replicated sensors. Once the sensors begin to dry out the variation decreases, again similar to the pattern observed with the Watermarks.

5.3.8 Electrical resistance sensors: response and hysteresis.

Between julian days 321 and 324, 35.6mm of rain fell on to the trial site (Table 5.3). The responses of the 3 replicates of both sensor types at 15 and 30cm have been plotted in Figure 5.20 to help assess the variation in responses between the sensors.

A large range in responses is observed for each sensor group. For instance, only one Watermark sensor (WM3) at 15cm depth shows any obvious wetting response (day 322). Two of the gypsum blocks wet up reasonably quickly, one from day 322, and the other from day 323, whilst the remaining gypsum block slowly wets up. If all rainfall had infiltrated into the soil and remained in the top 150mm of soil there would have been an increase of 35mm of water, or 23% of water by volume. However there is only a relatively poor response from both types of sensor.

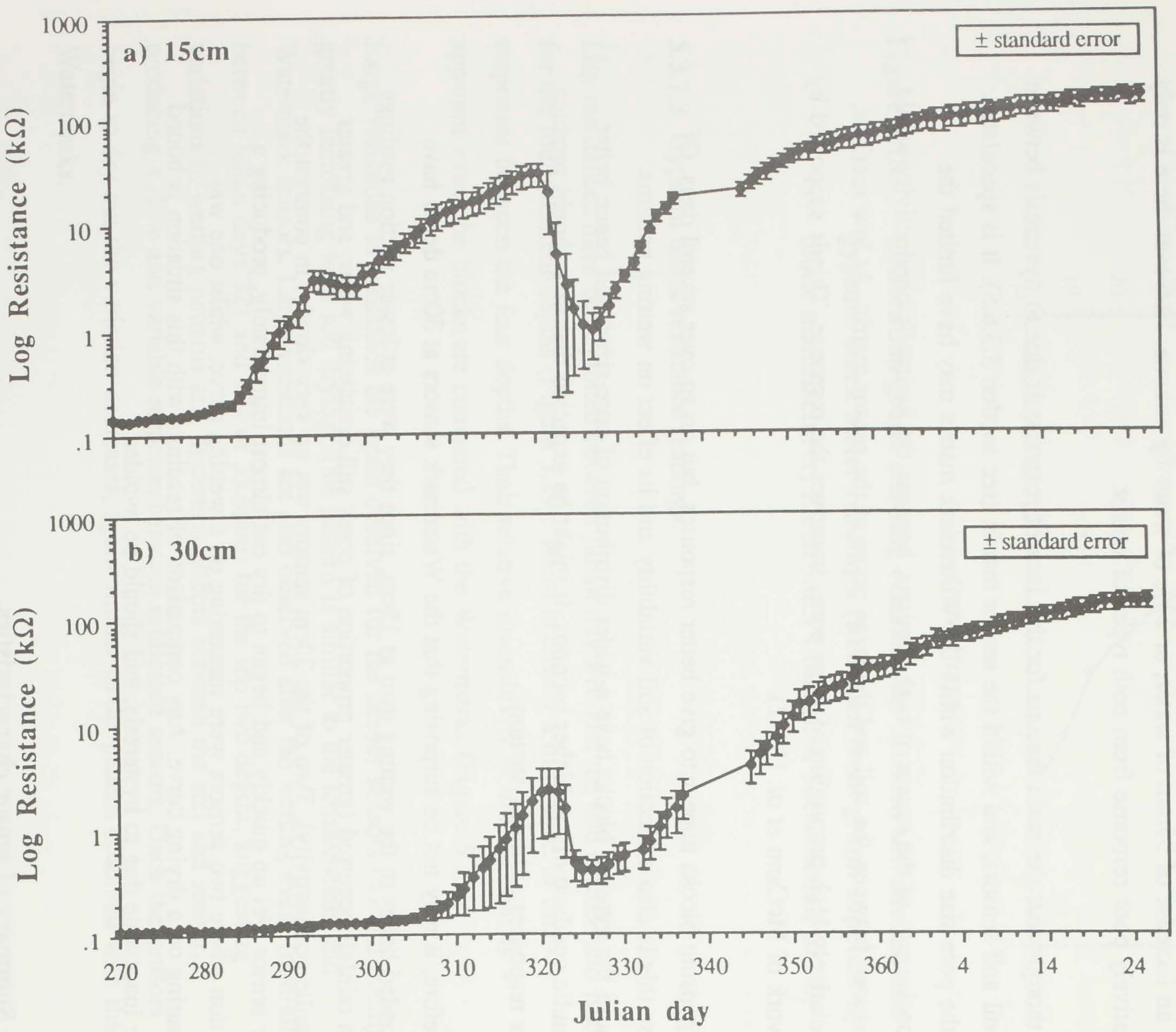
It is thought that the main reasons for this lack of response is due to hysteresis between the soil and sensors, and within the sensor matrix (see section 5.3.6.5). It is speculated that the pore-size distribution within the Watermark matrix may have limited the responsiveness of the sensor at high suctions, because the hydraulic conductivity would be reduced between the soil and the large pores of the sensor matrix. At low suctions, the relatively high proportion of large pores improves the response. This is supported by the work of McCann *et al.* (1992).

The gypsum blocks appear to give better responses, but do so over several days. Of course this is also a function of soil variability and its effect on wetting patterns. Because the gypsum blocks have a wider distribution of pore-sizes, and hence better hydraulic conductivity at higher suctions, it might be expected that they should produce better responses at higher suctions.

Therefore, it may not be surprising that the Watermark sensors at 30cm depth have responded better to the wetting than at 15cm, since they were at lower suction readings when rainfall occurred (greater proportion of pores still containing water, and greater hydraulic conductivity). Two of the 30cm sensors wet up very slowly, in contrast the other sensor wet up quickly and began to dry out almost immediately, producing a situation where two sensors were measuring on a wetting curve, whilst one was measuring on a drying curve. Any comparison of readings with this situation is bound to be inaccurate due to hysteresis, and should be avoided.

5.4. Summary of sensor characteristics.

Relevant soil moisture sensor characteristics for use in irrigation scheduling are summarised in Table 5.9. The table has been compiled from the findings of the field trial, and from the literature review.



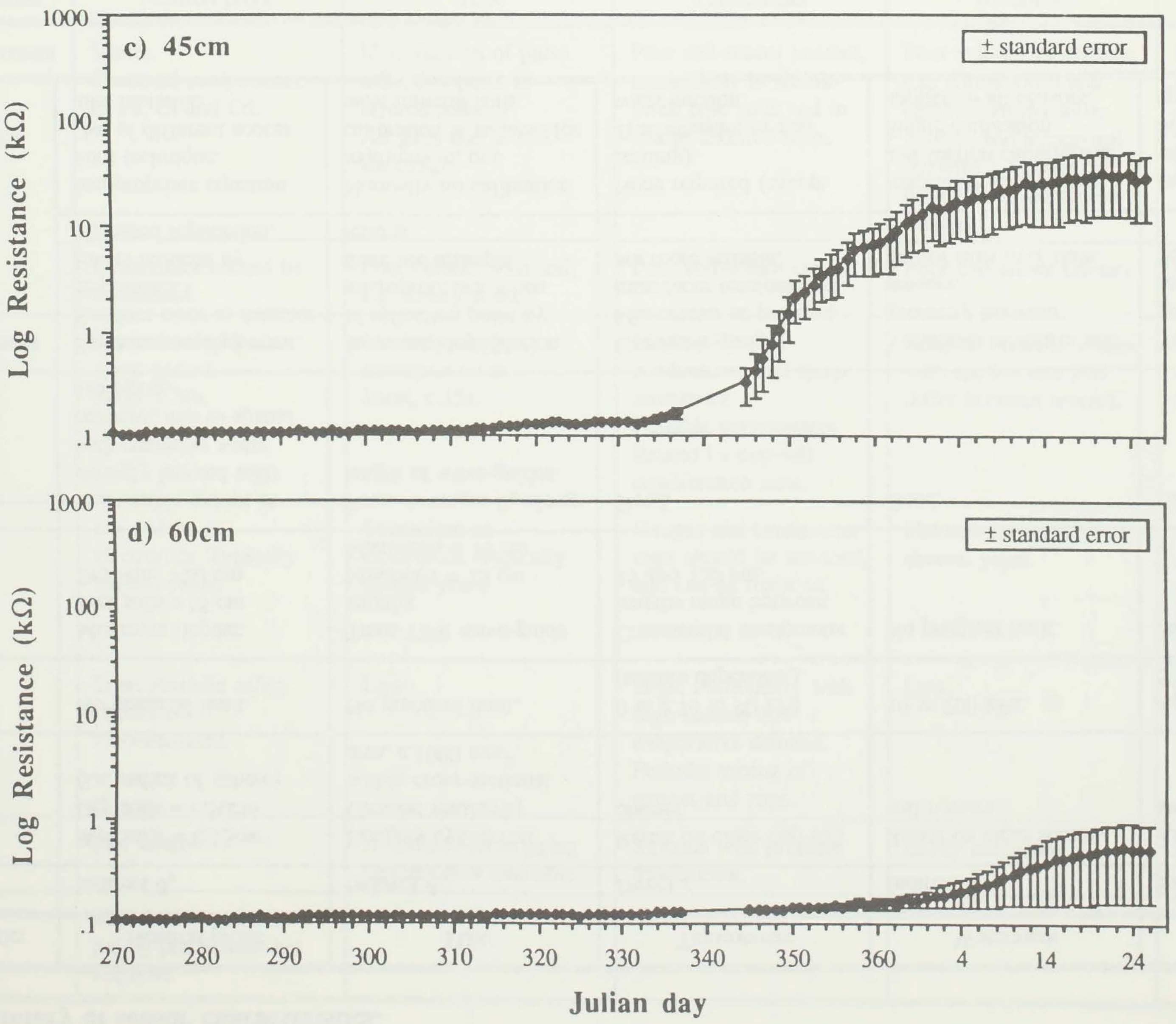


Figure 5.19: Gypsum block measurements between julian days 270 (1992) and 26 (1993).

Table 5.9: Summary of sensor characteristics.

Sensor characteristic:	Neutron probe	TDR	Tensiometer	Watermark	Gypsum block
"What it measures"	Indirect θ_v	Indirect θ_v	Direct *s*	Indirect *s*	Indirect *s*
Region of influence	Wet soils = c.15cm Dry soils = c.50cm (i.e. radius of sphere)	Roughly cylindrical. Greatest sensitivity within cross-sectional area, c.1000 mm^2	Relies on close cup-soil contact.	Relies on close sensor-soil contact.	Relies on close sensor-soil contact.
Soil moisture range	No practical limit.	No practical limit.	0 to c.70 to 90 kPa (texture dependent).	10 to 200 kPa.	Approx. between 30 to 50 kPa to 1 MPa.
Soil depth range	Minimum depths: Wet soils >15 cm Dry soils >20 cm	Trase TDR wave-guide lengths: Minimum = 15 cm Maximum = 70 cm	Commercial tensiometer lengths range between 15 and 150 cm.	No practical limit.	No practical limit.
Depth discrimination	Reasonable except in strongly layered soils with changing water contents, due to spatial averaging.	Poor. Averages θ_v along length of wave-guides.	Good.	Good.	Good.
Sources of measurement error: (i) instrument	Random counting error. Random error in detector electronics. Errors reduced by increased replication.	Incorrect identification of reflection point by microprocessor when there are multiple returns.	Unreliable gauges. Manometer or pressure transducer tensiometers are more reliable.	Variations in matrix and geometry between sensors. Sensor drift over time.	Variations in matrix and geometry between sensors. Sensor drift over time.
(ii) calibration	Inappropriate equation. Poor technique. Use of different access tube material.	Normally no calibration requirement, one calibration is suitable for most mineral soils.	None required (except zeroing). True measure of soil water suction.	Inaccurate temperature and suction calibrations. Single calibration applied to all sensors.	Inaccurate temperature and meter calibrations. Single calibration applied to all sensors.

Sensor characteristic:	Neutron probe	TDR	Tensiometer	Watermark	Gypsum block
Sources of measurement error (continued): (iii) soil morphology	Stones. Chemical components: B, Fe, Cl and Cd.	Identification of pulse reflection point in layered soils. Air gaps due to soil shrinkage.	Poor soil-sensor contact, more likely in shrink-swell type soils and in coarse textured soils.	Poor soil-sensor contact, e.g. shrink-swell and coarse textured soils. Sensor, and sensor-soil hysteresis. Greatest at high *s* with incomplete wetting.	Poor soil-sensor contact, e.g. shrink-swell and coarse textured soils. Sensor, and sensor-soil hysteresis.
(iv) installation	Disturbance should be minimized.	Poor contact with soil, e.g. stoney soils.	Poor soil-sensor contact.	Poor soil-sensor contact.	Poor soil-sensor contact.
Sensor response times	Limited only by the count period. Short, c.30s.	Limited only by microprocessor. Short, c.15s.	Limited by cup conductance and gauge sensitivity. Portable tensiometers limited by cup-soil equilibration time.	Response time increases with suction and will differ between sensors.	Response time increases with suction and will differ between sensors.
Sensor lifetime	Dependent on electronics. Typically several years.	Dependent on electronics. Typically several years.	Gauges and tensiometer cups should be serviced, and can be replaced.	Unknown. Probably several years.	Limited by gypsum dissolution. Several years in dry soils to < 1 year in wet, saline, or low pH soils.
Maintenance requirements	Low. Periodic safety checks are recommended.	Low.	High. Particularly with high suction and evaporative demand. Periodic testing of gauges and cups.	Low.	Low.
Automation	Not suitable.	Automatic datalogging systems now available.	Suitable with pressure transducers.	Easily automated.	Easily automated.
Other comments	Radioactive source. Safety precautions are required.				

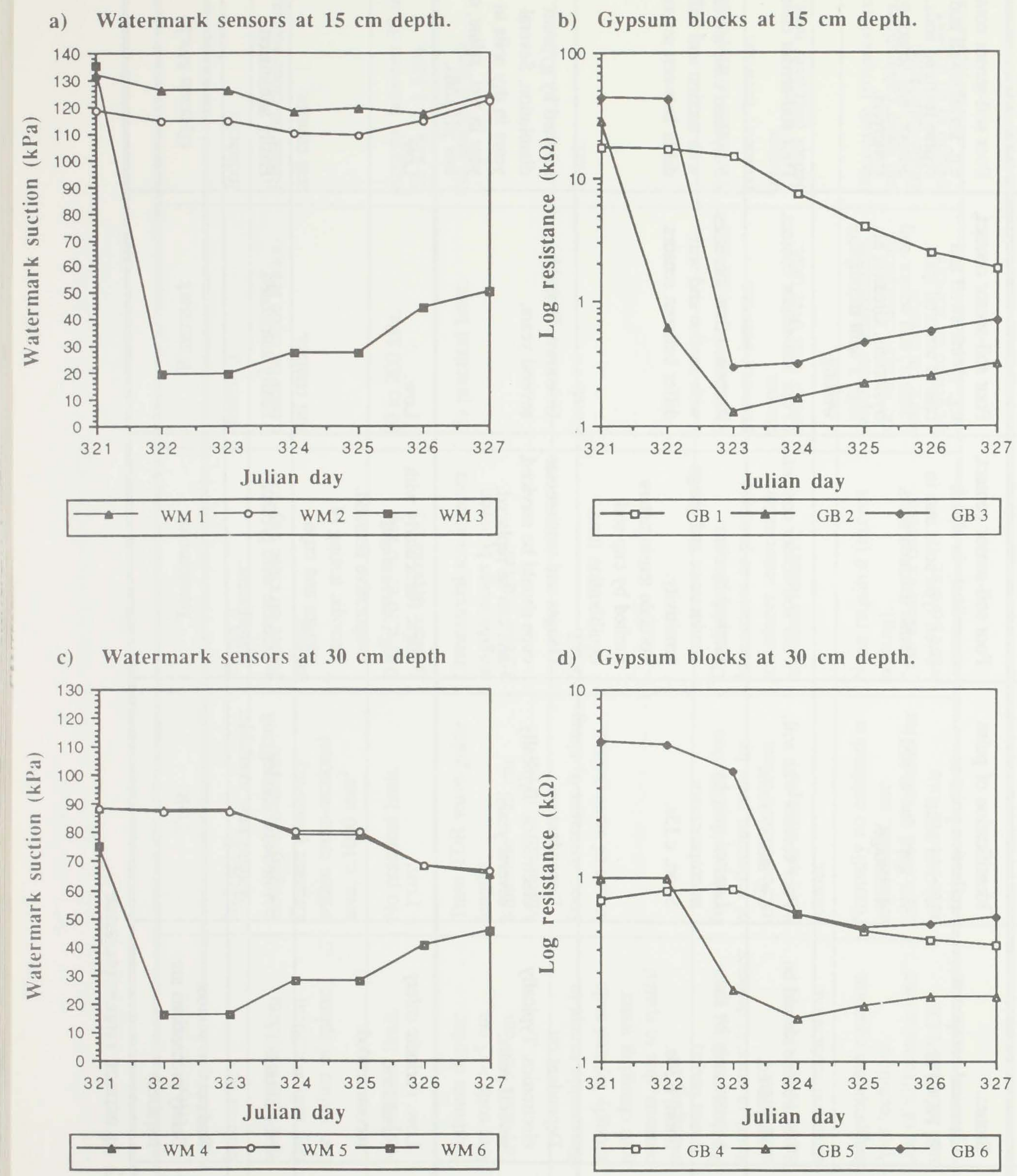


Figure 5.20: Resistance sensor responses following incomplete soil wetting.

CHAPTER 6 SELECTING SOIL MOISTURE SENSORS FOR IRRIGATION SCHEDULING.

6.1 Introduction.

To assess the suitability of a scheduling method that uses soil moisture sensors several factors need to be considered. These factors, discussed below, include soil and crop factors, the irrigation methods employed, the costs of sensors or irrigation scheduling service, and personal preference. Following the discussion the benefits and limitations of the individual soil sensors are listed to help select appropriate sensor(s). Practical considerations for site selection and the number of sensors to use are also discussed.

6.2 Considerations for sensor selection.

6.2.1 Crop factors.

a) Crop rooting depth.

The soil volume from which the plant extracts water is determined by its rooting distribution. Therefore, an estimate of rooting depth is essential for calculating the volume of plant extractable water, and the depth of irrigation required to replenish this reservoir. The rooting depth of annual crops increases to a maximum prior to attaining full crop canopy. Ideally the rate of root growth should be included in the calculation of allowable depletion, or trigger, levels. Simple estimates of rooting depth may be obtained by taking soil samples with an auger and examining them for live roots. Guides for characteristic maximum effective rooting depths for a range of crops have also been published (see section 2.3.3a).

Generally, vegetables tend to have shallow rooting systems which require light frequent irrigations. Deeper rooting arable crops do not require such frequent irrigation and can also withstand heavier irrigations.

b) Critical stress periods.

Plant water stress at certain periods of crop growth may affect crop yield more dramatically than at other times, and affect some crops more than others. Therefore it is important to avoid large soil moisture deficits at critical stress periods which result in large yield loss. This may affect sensor selection, particularly for shallow rooted crops. In this case the precision of the tensiometer or TDR may be desirable. A number of critical stress periods for a range of crops have been listed by Doorenbos and Pruitt (1977). In contrast over-irrigation can have considerable deleterious effects on some crops (e.g. peas). Crop sensitivity to over-irrigation may also be related to crop growth periods.

c) Regulated deficit irrigation (RDI).

The goal of deficit irrigation is to increase water-use efficiency; it deliberately allows crops to sustain some water stress and normally some yield reduction is accepted. It requires careful irrigation management to avoid any large yield loss. Therefore large soil water deficits at critical stress periods need to be avoided. Accurate monitoring of the soil water or crop indicators helps to minimise yield loss. Ideally both should be measured (English *et al.*, 1990). Managing soil water deficits is beneficial for some crop production, for example, limiting excessive vegetative growth in fruit trees, thereby reducing pruning needs.

Planning deficits at each irrigation, but small enough to avoid any large plant stress, may be a good practice in countries such as New Zealand, where irrigation tends to be supplemental, since it allows for additional rainfall which may fall soon after irrigation. Not only does this use rainfall more effectively, it reduces drainage losses and leaching, and minimizes waterlogging and aeration problems. Observation of the rainfall data during the course of the field trial (Table 5.3) indicates the irregular nature of rainfall during the growing period.

Therefore to manage deficit irrigation well, precise measurements of the soil water are necessary. It also requires fairly uniform irrigation applications. Large variations in irrigation applications may result in areas of the crop that become water stressed. Tensiometers would be unsuitable for deficit practices that accept yield loss because their upper suction limits (and associated high maintenance requirements) may be at the critical point at which stress begins.

d) Crop value.

High value crops, such as vegetables, that produce high economic returns require particularly careful water management. Irrigation should be aimed at producing

maximum marketable yield, whilst ensuring that normally high inputs of nutrients and chemicals, often added to the irrigation water (fertigation), are not leached out of the root zone.

e) Tubers.

Tubers (e.g. potatoes) are effectively large stores of plant water in the soil. Neutron probe measurements may be affected by the tuber water content. The TDR, because of its relatively small region of influence, will not be affected unless the rods are installed adjacent to a tuber.

6.2.2 Soil factors.

a) Soil variability.

The relationship between θ_v and ψ_m is strongly influenced by soil texture. Therefore large textural changes, vertically and laterally, within irrigation management units (IMU) will have significant effects on their irrigation management. An irrigation management unit might be a single cropping unit, or defined by limitations in irrigation equipment, or a change in soil type. Ideally each soil type should be managed separately, although this is not always feasible in practice. For example, variability may occur with irrigation practised on alluvial soils, similar to the soil of the field plot, which are inherently variable due to the processes that deposited the parent material.

Therefore, where soil spatial variability is high, the number of measurement sites and allowable deficit levels must be considered. If each soil type could be irrigated independently then optimum trigger points would differ, since allowable depletion levels would differ. Incorrect site selection may result in over-, or under-irrigation, and the associated reduction in yield and water-use efficiencies.

b) Soil layering.

Some of the problems related to soil layering have already been discussed (section 5.1). Clothier *et al.* (1977) have shown how water retention can be increased for soils underlain by coarser layers. Where this situation exists there are obvious advantages in using field measurements of plant-available soil water in preference to laboratory estimated ones (section 2.4).

Shallow poorly permeable layers, such as cultivation plough pans, may become waterlogged, and associated aeration and rooting problems may develop. This may not strictly be an irrigation scheduling problem, rather a cultivation management one. The problem may be diagnosed by sharp changes in the soil water profile. Sensors that discriminate moisture contents, or suctions, between depths can be used to identify this problem.

c) Stones.

Stones are a problem for the installation of all these sensors, particularly if deep measurements are required. Neutron probe access tube installation may be practically impossible.

TDR sensitivity to air gaps next to the wave-guides, which may be caused by installation in stony soils, prevents its accurate use in these types of soils. The suction sensors can normally be installed, but with some difficulty.

d) Shrink-swell soils.

Shrinking of the soil may present some problems in using the TDR because of soil cracking. These types of soils present considerable management problems because of their typically low hydraulic conductivity, and because of non-uniform wetting patterns if the soil is allowed to crack.

e) Salinity.

New Zealand does not suffer from the types of salt problem associated with irrigation in other countries. High salt concentrations will affect the use of the electrical resistance sensors, despite their buffering capacity. Gypsum will dissolve more quickly in these conditions. Saline conditions will also increase TDR signal attenuation (i.e. decrease the precision). The neutron probe and tensiometers will be unaffected, although the tensiometer will fail to measure the osmotic component of soil water potential, which contributes to plant stress.

6.2.3 Irrigation methods.

Both field water application efficiency and irrigation application uniformity vary greatly between irrigation methods. Reasons include: equipment limitations; weather conditions; crop cover; soil surface condition; irrigation application rates and soil infiltration rates. Here, application efficiency is defined as the ratio of the water directly available to the crop, to the amount of water applied to the soil by irrigation.

a) Overhead irrigation.

Large variations in irrigation application uniformity may be experienced from overhead irrigation. A study of eleven New Zealand manufactured travelling irrigators produced coefficients of uniformity (C_u) of between 69 and 96%, with application rates of between 9 and 78 mm hr^{-1} (NZAEI, 1985). The coefficient of uniformity is calculated by the equation

$$C_u = 100 \left\{1 - \frac{\Sigma x}{m.n}\right\} \qquad 6.1$$

where, x are the deviations of application depths from the mean depth, m is the mean depth, and n is the number of observations.

Not surprisingly, this study also found that high application rates often exceeded the soil infiltration rate and resulted in surface ponding. As a result, uneven soil wetting is likely to occur due to preferential flow of the surface water down soil cracks and bio-pores. Several factors that affect application uniformity, include: wind speed and direction, pressure drops along sprinkler laterals, incorrect pump pressures, incorrect sprinkler head spacing, and worn nozzles.

Poor uniformity and ponding will also result in reduced application efficiency because of drainage losses from the root-zone. Within the root zone there will be some redistribution of soil water between soil layers, predominantly by gravitational flow. Clothier and Heiler (1983) showed that under very high irrigation application rates, surface re-distribution of free water can lead to very non-uniform soil wetting. This non-uniformity was considerably greater than that of the application pattern itself. Figure 6.1 (from Clothier and Heiler, 1983) shows the different wetting patterns several hours after irrigation applied at 2 different rates: (i) at 102.5 mm hr^{-1}, and (ii) at 4.1 mm hr^{-1}. The soil saturated hydraulic conductivity (K_s) was measured as 10.9 mm hr^{-1}.

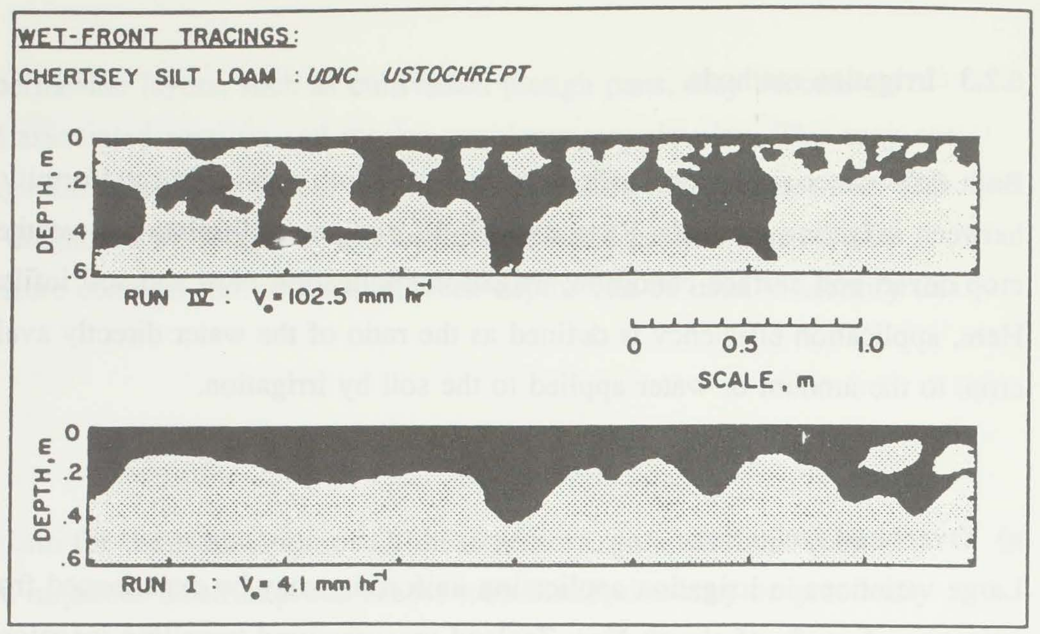


Figure 6.1: **Tracings of the wet front several hours after sprinkler irrigation at two application rates: (i) at 102.5 mm hr^{-1} and (ii) at 4.1 mm hr^{-1}. From Clothier and Heiler (1983).**

Non-uniform soil wetting under rainfall has also been observed in a Templeton silt loam in Canterbury (Webb, 1989). He suggested that mechanisms similar to those proposed by Clothier and Heiler (1983) were causing the non-uniform wetting. K_s (not measured) was believed to be very low due to surface crusting.

This illustrates the problem of using soil water balance methods which require the depth of irrigation that has been applied. Inaccurate estimates of overall application depths due to application non-uniformity can cause serious error in the water balance. By the nature of the soil water balance method these errors are cumulative, if no soil water measurements are made. Using rain-gauges or catch cans will indicate the sprinkler uniformity. Increasing the number of soil-based sensors will help indicate the soil water spatial variability.

Webb (1989) suggests strategies for the management of non-uniform wetting. For crops that are sensitive to excess water then optimum irrigation depths should be lower than if the wetting is uniform. The opposite is true if crop yield is not sensitive to excess water. However the latter case means an increase in water and power costs, and possibly excess irrigations, because of no allowance for rainfall.

Soil moisture content sensors can be used to assess the amount of water that has been stored in the root zone and the amount of water that has been effectively lost to the

crop because of deep percolation. Soil suction sensors will be able to detect the downward flux of draining water. Thus suction sensors below the root zone will be able to detect whether there are any deep percolation losses.

Automation of overhead, centre-pivot irrigation systems using tensiometers has been described by Thomson and Threadgill (1987), who also proposed Watermarks as a maintenance-free option. Watermark-based control has also been recommended for landscape irrigation (Pogue, 1990).

b) Surface irrigation.

Border strip irrigation is predominantly used in the New Zealand community irrigation schemes, and water is allocated by fixed rotation. Values for irrigation application efficiencies for these schemes have not been found, but a wide range is expected because of the range of soils, and their infiltration properties. Typical application efficiency (Ea) values quoted by Doorenbos and Pruitt (1977) found overseas are between 0.53 and 0.75 for a graded border.

Fixed rotation, or rostering, is a great limitation for scheduling surface irrigation, since it is seldom possible to apply irrigation at the optimum time (Rickard and McBride, 1986). A tendency to irrigate border-strips, in New Zealand, even when yield response is negligible in the Spring and Autumn has been noted by Dent (1985). This practice is likely to cost more in nutrient leaching than any yield benefits.

Mismatching the application rate with the soil infiltration rate will result in poor uniformity. As with overhead irrigation, good application uniformity will result in more reliable schedules. Soil moisture sensors might be used to identify this problem, which may not have been obvious, and adjust the irrigation practice. Because most of New Zealand's irrigated soils are shallow and have high infiltration rates (Taylor, 1981) the likelihood of excess irrigation is high.

c) Micro-irrigation (trickle and micro-sprinklers).

Scheduling methods for trickle irrigation may be quite different because the soil is used more as a transmission medium rather than for water storage, and because water application is more strongly localised.

Soil moisture sensors are important because they can monitor the wetting pattern of the emitters, ensure water is available to the plant, and that drainage losses are kept to a minimum. Good management of a trickle system can achieve Ea values of close to one. Therefore siting of sensors is a critical consideration. Ideally suction sensors should be used to detect the direction of water movement. Gypsum blocks would not be appropriate within the wetting bulb, but could be used in combination with tensiometers (or Watermarks) within the bulb. Instead gypsum blocks could be installed on the outside of the bulb to measure whether the water is being applied efficiently. Scotter and Clothier (1986) describe a marked water content gradient between the trickle source and the wetting front. The soil close to the wetting front was always considerably drier.

Automation of micro-irrigation systems using soil moisture sensors to schedule is now possible. One commercial trickle system that uses tensiometers to trigger a set volume of irrigation, and used in practice by a tomato grower, in New Zealand (Lok, 1992).

Micro-sprinkler, like trickle, irrigation is a high frequency, and potentially high application efficiency system. Similarly monitoring of the soil water is required to avoid drainage losses and supply adequate water. Generally, low suctions will be maintained, although RDI may also be practised (e.g. in orchards to reduce vegetative growth). Water content sensors may therefore be equally as appropriate as soil suction sensors.

Pressure loss along micro-sprinkler laterals may result in variation of application depths, and this needs to be considered when selecting a measurement site. Poor maintenance of drippers and sprinklers (e.g. because of clogging) will also result in poor uniformity.

6.2.4 Costs.

a) Sensor costs.

The approximate costs for the individual sensors used in the field trial are listed below, in Table 6.1.

The costs of the sensors, or use of a scheduling service, should be weighted against the opportunity costs of not using the sensors. For example: pumping, water, and nutrient and chemical leaching costs which result from excess irrigation draining below the root-zone; labour costs incurred due to an unnecessary irrigation; and reduced marketable yield or quality because of water stress, or over-irrigation.

Experiences of irrigation scheduling consultants in Canterbury have revealed that growers were not achieving maximum yields because they had tended to irrigate after the crop had become stressed, and then to over-irrigate resulting in drainage losses (R. Day pers.comm.; I. McChesney pers.comm.).

A further cost which has not been adequately explored in New Zealand is the environmental cost of poor irrigation management. However there is evidence that nitrate leaching from irrigated crop production has lead to rises in groundwater nitrate levels (Bowden, 1982). A recent leaching study has shown that under simulated border strip irrigation drainage water nitrate levels under urine patches exceeded WHO recommendations for drinking water (Fraser, 1992).

It should be noted that elsewhere in the world severe irrigation-relate environmental problem have occurred due to poor irrigation management. For example: elevated water tables and salinity levels in Pakistan; salinity and sodicity problems in Australia; drainage water toxicity problems in California. Clothier (1989) commenting on these problems, suggested that it was the world trend to over-irrigate.

Interestingly, the present project has a 'mirror image' counterpart in the research station Queckbrunnerhof in Germany, where the same set of scheduling methods (weather stations, TDR, neutron probe, Watermark, gypsum block and tensiometer) is being explored. The objective there is related to 'environmental protection', by reducing leaching of fertilisers and pesticides to groundwater (Dr. J. Maync, pers. comm., 1993).

6.2.5 Personal preference.

The final choice of scheduling method, sensor type or scheduling service, rests with the grower. Government policy in New Zealand has meant that all farm management costs are now the responsibility of the grower. In contrast, in the USA, most extension, including irrigation scheduling, is wholly or partly subsidised by government.

Irrigation scheduling, like most other farm management activities, involves time and effort. However the consequences of maximizing profits, and using resources more efficiently, are likely to outweigh this limitation. Using soil moisture sensors and irrigation scheduling will also encourage greater understanding of the interactions between the plant and the soil. For example, soil sensors can indicate problems below the soil surface, such as the effect cultivation pans or naturally-induced poorly permeable layers.

The time taken to schedule irrigations is dependent on 3 main factors:

1) The type of scheduling methods used, i.e. soil-based, crop-based, or soil water balance methods (manual or computerised). If sensors are being used, the type and number of sensors and sites may vary measurement time (discussed below).

2) Distance between sites.

3) Number of irrigation decisions to be made. This is dependent on the number of irrigation management units, and the equipment or water rostering limitations (i.e. for border-dyke).

The average time taken to schedule irrigations using a neutron probe method, using a graphical recording approach similar to one described by Gear *et al.* (1977), has been recorded by one Canterbury neutron probe scheduling consultant. It took an average of 16 minutes to schedule one irrigation block with two access tubes (I. McChesney pers. comm.). The reading time for the neutron probe is greater than for the other sensors assessed in this thesis. The sensor 'one-shot' measurement time may vary between sensors, according to manufacturer, but normally the minimum time is about 30 seconds for a single depth reading).

a) Installation time and effort.

Soil type and current moisture status affect both the time and effort required to install the sensors. Methods for installation have been described in Chapters 3 and 4. Generally moist conditions will allow easiest installation of all sensors.

b) Using scheduling services.

The demand for irrigation scheduling services in New Zealand has been increasing (see Chapter 1), for field crops, pasture, and horticultural crops.

Costs of services vary depending on the number of sites being monitored, travel time and distances, and crop type. For example, in Canterbury, average moni'oring periods

for pasture (for dairying) and field crops are approximately 25 weeks and 10 weeks, respectively, with a measurement interval of 1 week or greater if there was significant rainfall (R. Day pers. comm.). One orchard grower estimated the cost per ha of the scheduling service as approximately \$125 ha^{-1} (Wardle, 1991). Another estimate for a arable farm with 4 irrigation management units (IMU) was approximately \$260 per IMU per season (R. Day pers. comm.).

Growers use the services for a variety of reasons. Typical motivations, reported by some of the scheduling consultants in Canterbury, include: improved yield, improved crop quality (particularly horticultural crops), ensuring adequate irrigation, preventing over-irrigation, the reduction of water or pumping costs, and quite simply 'peace of mind'. Growers may also value the contact with the scheduling consultants, wishing to discuss a variety of issues not necessarily associated with the irrigation scheduling (Hess, 1990; R. Day and I. McChesney pers. comm.).

6.3 Summary of the suitability of the investigated sensors for irrigation scheduling.

The tables (6.1.a to e), below, are based on a format used by Campbell and Mulla (1990) to help describe the benefits and limitations of the soil moisture sensors for a range on conditions that may be encountered.

Table 6.1: **Summary of the suitability of the evaluated sensors for irrigation scheduling.**

a) Neutron probe.

Appropriate for:	Inappropriate for:	Advantages	Disadvantages
a) Crops: Moderately shallow to deep rooting crops (i.e. most horticultural and agricultural crops).	Tuber or dense rooting crops. Very shallow rooting crops, or turf grass.	A precise method for changes in soil moisture. Accurate when properly calibrated. Repeated measurements at same site and depth. Good depth resolution for small spatially averaged samples.	Unable to measure soil water separately from water held in tubers. Installation problems in stony soils. Radioactive source. Calibration required for each soil type for accurate measurement. Costs: Probe - c. NZ$12,000 to 15,000. Access tubes - c.NZ$10.
b) Soils: Uniform soils of all textures.	Surface measurements (0 to 15 or 20 cm). Very stony soils with high B, Fe and Cl. Stony soils.		
c) Irrigation method: Flood, overhead and microsprinkler irrigation. Full or deficit irrigation.	Trickle irrigation. Automation.		

b) TDR.

Appropriate for:	Inappropriate for:	Advantages	Disadvantages
Crops: Crops rooting to approx. < 70 cm.	Deep rooting crops (>70 cm).	Accurate. (±2% θ_v) No calibration required. Repeated measurements in situ. Can be used to rapidly assess spatial variability. Average θ_v over length of wave-guides. Portable.	High cost probe - c. NZ$13,000. wave-guide pair - c.NZ$4 Vertical wave-guides have poor depth resolution. Stony soils should be avoided. Very sensitive to air gaps around wave-guides. Maximum depth 70 cm (Trase model).
Soils: Uniform soils. Initial assessment of spatial variability for sensor site selection.	Soils with highly contrasting textural layers. Stony soils.		
Irrigation method: Overhead and flood.	Trickle irrigation.		

c) Tensiometer.

Appropriate for:	Inappropriate for:	Advantages	Disadvantages
Crop: Water sensitive crops: e.g. vegetables.	Crops that may become stressed, e.g. some cereals.	Accurate when properly maintained. Relatively low cost - c.NZ$120 Repeated measurements. Easily installed. Instantaneous reading.	High maintenance requirement. Maximum suction range 0 to 85 kPa (or less).
Soil: Fine to coarse textured soils.	Very stony soils. Shrink-swell soils. Very coarse textured soils or gravels.		
Irrigation method: Overhead, trickle and flood. Full irrigation, or high frequency irrigation. Automation.	Deficit irrigation.		

d) **Watermark.**

Appropriate for:	Inappropriate for:	Advantages	Disadvantages
a) Crop: All crop types.	Crops that may become stressed, e.g. some cereals.	Relatively low cost: sensor - c.NZ$60 meter - c.NZ$550. Repeated measurements. Easily installed.	Variability between sensors. Sensor hysteresis. Some sensor drift. Soil temperature should be measured to improve accuracy. Matrix will not dissolve. Slowed response toward the dry end of range (s>120 kPa). Possible soil-sensor contact problems in very coarse textured soils.
b) Soil: Fine to medium textured soils.	Very coarse textured soils. Permanently water logged. High salt contents.	Instantaneous reading. No depth limitation. Easily automated. Wider range than tensiometers (c.10 to 200 kPa).	
c) Irrigation method: Methods that return the soil to DUL. Automation.	Deficit irrigation where soils are not returned to DUL.	With care may be installed in stony soils. Sensor matrix will not dissolve.	

e) **Gypsum block.**

Appropriate for:	Inappropriate for:	Advantages	Disadvantages
a) Crop: Dryland type crops - may be stressed. Siting below the root zone to assess deep drainage.	High value crops, e.g. vegetables. (unless sited below the root zone).	Low cost: sensor - c. NZ$12 meter - c. NZ$400. Repeated measurements.	Insensitive to low suctions (<30 to 50 kPa). Variability between sensors. Sensor drift. Sensor hysteresis. Matrix dissolves over time. Temperature compensation required to improve accuracy. (No correction circuit with this meter). Possible soil-sensor contact problems in very coarse textured soils.
b) Soil: Fine to coarse textured.	Very coarse textured soils.	Easily installed. Instantaneous reading. Easily automated. With care may be installed in stony soils.	
c) Irrigation method: Sprinkler and flood.	Trickle. High frequency (shallow cycle) irrigation.		

6.4 Recommendations for practical use of the sensors for scheduling.

The considerable benefits of using soil moisture sensors for irrigation scheduling have been illustrated above. In particular they allow a scheduler to "see" what is going on below the soil surface, and this can be related to the performance of the crop. Ideally crop indicators should be used in conjunction with soil monitoring.

6.4.1 Number of sensor stations.

Campbell and Campbell (1982) suggest that only one "representative" measurement site (or station) is required for soil water monitoring for each field (or irrigation management unit, IMU). Since the field is often irrigated as a single unit then only one representative site is required.

This may well be adequate for a uniform soil where irrigation is uniformly applied. However, because of the large variability of wetting associated with poor application uniformity, or changes in soil types across the IMU, it may be more appropriate to have more than one "representative" station. This will allow better assessment of the irrigation scheduling and will allow some adjustment to be made. It has been established that poor irrigation application uniformity and excessively high application rates may cause large errors in estimating soil moisture (section 6.2.3).

The main disadvantage of using more than one station is the cost of the sensors (or scheduling service). There will also be additional time required for sensor measurement. However it would provide a much better understanding of the soil water relations, and any irrigation application problems. Large differences in the amount of plant-available water between sites may still mean that one site will be under-irrigated whilst another is over-irrigated. However, using more than one station should contribute to greater optimisation of crop yield.

It is recommended that two, or more, sensor stations should be used for border-strip irrigation: one approximately a third of the distance from the top of the strip, and the second a third from the bottom of the strip. This is in preference to using one station as suggested by Campbell and Campbell (1982), set about a half to a third of the distance from the top of the strip. Using two stations allows the irrigator to monitor whether there is adequate irrigation at the bottom of the strip, whilst minimising drainage losses at the top of the strip. Using such sensor measurements it should be possible to modify flow rates and water depths to be applied.

Initial assessment of soil water spatial variability using the TDR (Campbell, 1990) may be a good means of selecting appropriate sensor stations. Similarly portable tensiometers might be used. However, portable tensiometers should only be used when suctions are close to zero (section 3.3.7). Exploiting the portability of the TDR, and ease of rapid insertion of wave-guides under certain conditions, wave-guides can be inserted for individual measurements at several depths at different locations within the irrigation unit. This would be applicable to shallow measurements, in soils that allow easy insertion. Longer wave-guides (e.g. 50 to 70 cm lengths) may prove difficult to install. Alternatively, these longer wave-guides could be permanently installed.

Sensor sites should be situated amongst actively growing, healthy plants, and in a location exposed to normal climatic conditions. Crop edges should be avoided. This is particularly important in orchards and crops surrounded by shelter belts because of intensive competition for water.

6.4.2. Sensor numbers and measurement depths.

a) Measurement depths.

Firstly the strategy for triggering irrigation should be decided. This will be partly determined by the type of sensor used i.e. the neutron probe and TDR measure θ_v, whilst tensiometers and electrical resistances measure suction, *s*. Soil water content methods typically use a measure of soil water deficit over a pre-determined depth (i.e. the effective rooting depth) to trigger irrigation. Whereas, soil water suction methods will usually use a pre-determined suction level read by a sensor(s) for a set depth within the rooting zone. These trigger points and depths may change through the growing season.

In a shallow-rooting crop (< 50 cm) sensors should be placed at a minimum of 2 depths. The shallowest should be within the active rooting zone, approximately mid way. Whilst the deeper measurement should be made at the bottom of or slightly below the expected limit of effective rooting.

For deeper rooting crops (> 50 cm) at least three depths are recommended. Again the deepest should be located at the bottom, or slightly below, the root-zone. Others should be placed in the region of active rooting. For example, for a crop that has a maximum

effective rooting depth of 1 m. the appropriate sensor measuring depths might be 30, 60 cm and approximately 1 m.

The maximum wave-guide length limitation of the TDR probe has already been discussed (3.2.4) and has been described as a limiting factor for its use as a scheduling tool (Table 6.1). However if used in conjunction with other sensors (e.g. electrical resistance sensors) its use may be appropriate. This type of approach would use TDR θ_v measurements to schedule irrigations and use a suction sensor at depth to indicate whether there are drainage losses from the bottom of the root zone.

Sensors should be installed at several depths (normally three) so that the water potential gradient can be monitored, and irrigation adjusted accordingly. Tensiometers are the most practical sensors for this type of monitoring.

b) The number of sensors required.

Ideally there should be more than one replicated sensor at each depth, for each sensor station. The effects of sensor variability and soil spatial variability have been shown in the field trial. There will obviously need to be a compromise between the precision of the measurements (by increasing the number of replicated sensors) and the cost of the sensors. It is suggested that at least two sensors should be used at each measuring depth. Alternatively, only sensors at depths used for triggering irrigation should be replicated. Where irrigation application uniformity is poor, this number should be increased.

Replicated sensors (at one sensor station) should be relatively closely spaced (e.g. <50 cm apart) to help reduce soil and irrigation spatial variability effects. As the field trial showed, soil spatial variability affected soil moisture measurements even within this small area.

6.4.3. Measurement interval.

Measurements are generally taken once a week by the irrigation scheduling consultants using neutron probes in Canterbury (section 6.2.5). Based on these readings they make their scheduling recommendations. In most cases weekly readings will be adequate for all the sensor types. However, "on-farm" monitoring allows greater flexibility, i.e. the measurement interval can be adjusted according to the stage of crop growth, the prevailing weather conditions, and from the 'first hand' experience gained from the regular monitoring of the soil water content or suction. As described above (section 5.3.4.2), tensiometers will require more regular monitoring as the suction increases. Monitoring and purging every two or three days may be necessary when evapotranspiration is high.

CHAPTER 7 SUMMARY AND CONCLUSIONS

7.1 Summary.

1. The objectives of the research project were to:
   (i) evaluate five soil moisture sensors, namely, the neutron probe, TDR probe, tensiometers, Watermark sensors and gypsum blocks, for use as irrigation scheduling tools, particularly in New Zealand conditions; and
   (ii) recommend methods for their practical use in irrigation scheduling.

2. The principles of irrigation scheduling (for soil, plant and soil water balance based methods) are reviewed. The sensors being evaluated are also reviewed. Particular reference is made to their practical benefits and limitations (e.g. measurement range, depth limitations, sensitivity to temperature, salinity and soil type, accuracy, durability and installation and maintenance requirements).

3. The objectives of the field trial were, firstly, to evaluate the characteristics of the sensors in relation to irrigation scheduling, and secondly, to assess the effects of inter-sensor measurement variability within each of the five types of sensor.

4. Excavation of the field plot, after ten months of sensor measurements, illustrated some of the problems of soil spatial heterogeneity and helped explain some of the sensor measurement variability.

   Both the neutron probe and the TDR probe performed reliably throughout the trial period. Both instruments produced precise readings, although there were differences between their measurements in the same soil layers. However, this is not necessarily a problem for irrigation scheduling, since it is the relative changes of soil water depletion that are important.

   Using replicated TDR wave-guides it was possible to discriminate moisture contents within individual depth layers. However this was shown to be less precise than neutron probe depth discrimination, due to the inevitable spatial separation of the pairs of wave-guides used for the TDR method.

The Watermark electrical resistance sensors performed well. Inter-sensor variation makes these sensors generally less precise than tensiometers. Replication of the Watermarks, and use of the manufacturers' meter calibration for soil water suction, gave good agreement with tensiometer-measured read suction, for sensors at 30 cm depth. The Watermarks have some advantages over tensiometers, for example, Watermarks do not require maintenance, whereas the tensiometers required frequent maintenance particularly at high suctions, especially when PET demand was high. Watermarks can also be easily automated, and have a slightly wider range than tensiometers.

Both types of electrical resistance sensor (the Watermark and gypsum block) require temperature correction for precise measurement. It is suggested that gypsum block meters should have built-in temperature correction circuits, like the Watermark.

Problems of electrical resistance sensor hysteresis were observed, especially when the sensors were measuring high suctions under partial re-wetting of the soil.

5. The sensor characteristics that are of practical importance to irrigation scheduling are discussed. Irrigation method and strategy (e.g. full or deficit irrigation), crop type, soil type, and the role of the grower's personal preference are all considered in relation to the selection of scheduling technologies.

   It is concluded that the effects of application non-uniformity, high irrigation application rates and soil spatial heterogeneity can contribute large errors to irrigation scheduling. These are likely to greatly exceed any soil water measurement errors as a result of sensor variability.

6. Recommendations are made for the practical use of the sensors in the field. These are largely qualitative, but based on the experience of the field trial and other workers. Site selection, the number of measurement sites, appropriate measurement depths and number of replicated sensors (or measurements) are all discussed and recommendations made.

7.2 Conclusions.

1. Soil moisture sensors are very valuable scheduling tools, particularly in countries such as New Zealand where irrigation is supplementary to rainfall. Therefore soil-based scheduling is strongly recommended Often, the water budget method is used. However, because of cumulative errors in the soil water budget method, often greatest because of inaccurate measurements of rainfall and irrigation, soil moisture measurements should be used as a supplement to check the reliability of water budget calculations.

2. The TDR probe is a simple, easy to use, alternative to the neutron probe. It has several advantages over the neutron probe, including: easy, quick assessment of the spatial variation of soil water; it is non-radioactive; greater portability; ability to measure reliably in the surface layers; and it does not require a calibration for accurate measurement. Its major limitation are a) inaccuracies in depth-resolved layer water contents; and b) the depth of measurement (the "Trase" TDR probe has a maximum wave-guide length limit of 70 cm). However the solution to this latter problem would be to use the probe measurements in conjunction with measurements from another sensor type (e.g. gypsum blocks).

3. Tensiometers are probably the best suited sensors for high frequency, shallow-cycle irrigation, where precise measurements are required, provided they are well maintained. However the Watermark sensor has proved a promising alternative, and has the added advantage of a greater suction range (c.10 to 150 kPa).

4. Gypsum blocks are most appropriate for 'dryland' crops that may be allowed to suffer some water stress. Usually these are lower-value crops. The blocks should also be replicated for increased precision. In addition, installation of these sensors at the bottom of the effective root-zone, to monitor potential drainage losses, would be appropriate for most irrigation strategies.

5. One of the greatest irrigation water management problems in New Zealand, which complicates irrigation scheduling, is the often poor application efficiency of all types of irrigation (surface, overhead and micro-irrigation). Travelling overhead application rates tend to be high, and for most soils will be in excess of the infiltration rate.

7.3 Future research.

Several areas for future research, related to the use of soil moisture sensors, and to the general application of irrigation scheduling in New Zealand, have been identified.

1. The potential for the automation of irrigation scheduling using soil moisture sensors needs to be assessed. Commercial automated systems are already available (for tensiometers and Watermarks), however little has been reported about their practical applications.

2. Newly developed soil moisture sensors require field evaluation, e.g. capacitance type probes which are now manufactured in the USA and Australia, and an optically-based method of measuring soil water suctions recently described in the literature (Cary *et al.*, 1991).

3. The problems of poor application efficiency for the range of irrigation methods require addressing, in both New Zealand and overseas. Quantification of drainage losses, and nutrient and chemical leaching are required.

4. Despite the known benefits of irrigation scheduling, it is poorly practised in New Zealand. Therefore, greater effort is required to extend improved water management practices to the grower. To accomplish this research will be required into (i) the adoption patterns of the irrigators, and (ii) the best methods for extension of appropriate irrigation scheduling practices.

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APPENDICES.

Appendix 1 CR10 datalogger program for the electrical resistance sensors in the field. The program was written using the 'Edlog'software, part of the PC208 package (Campbell Scientific, Inc.).

1.1 Program 1: Sensor measurement and output every four hours.

Program:	Field data
Flag Usage:	Output every 4 hours
Input Channels:	AM32 in Ch. 1, Temperature in Ch.2-6).
Excitation Channels:	AM32 in Ex. 1, Temp in Ex. 2.
Control Ports:	AM32 in Port 5
Pulse Input Channels:	AM32 Clock in Port 6

```
*     1        Table 1 Programs
  01: 3600     Sec. Execution Interval
01:  P92       If time is
  01: 0        minutes into a
  02: 240      minute interval
  03: 30       Then Do
02:  P17       Module Temperature
  01: 27       Loc :
03:  P10       Battery Voltage
  01: 28       Loc :
04:  P11       Temp 107 Probe
  01: 5        Reps
  02: 2        IN Chan
  03: 2        Excite all reps w/EXchan 2
  04: 1        Loc :
  05: 1        Mult
  06: 0        Offset
05:  P20       Set Port(s)
  01: 9991     C8..C5=nc/nc/nc/high
  02: 9999     C4..C1=nc/nc/nc/nc
06:  P87       Beginning of Loop
  01: 0        Delay
  02: 21       Loop Count
07:  P86       Do
  01: 76       Pulse Port 6
08:  P5        AC Half Bridge
  01: 1        Rep
```

02: 14 250 mV fast Range
03: 1 IN Chan
04: 1 Excite all reps w/EXchan 1
05: 250 mV Excitation
06: 6-- Loc :
07: 1 Mult
08: 0 Offset
09: P95 End
10: P20 Set Port(s)
01: 9990 C8..C5=nc/nc/nc/low
02: 9999 C4..C1=nc/nc/nc/nc
11: P59 BR Transform Rf[X/(1-X)]
01: 21 Reps
02: 6 Loc :
03: 1 Multiplier (Rf)
12: P86 Do
01: 10 Set high Flag 0 (output)
13: P77 Real Time
01: 110 Day,Hour-Minute
14: P70 Sample
01: 28 Reps
02: 1 Loc
15: P95 End
16: P End Table 1

1.2 Program 2: Measurement and output every 24 hours.

Program:	Field data
Flag Usage:	Output every 24 hours at 0800
Input Channels:	AM32 in Ch.1, Thermistors in Ch.2-6).
Excitation Channels:	AM32 in Ex. 1, Temp in Ex. 2.
Control Ports:	AM32 in Port 5
Pulse Input Channels:	AM32 Clock in Port 6

* 1 Table 1 Programs
01: 3600 Sec. Execution Interval
01: P92 If time is
01: 480 minutes into a
02: 1440 minute interval
03: 30 Then Do
02: P17 Module Temperature
01: 27 Loc :
03: P10 Battery Voltage

01: 28 Loc :
04: P11 Temp 107 Probe
01: 5 Reps
02: 2 IN Chan
03: 2 Excite all reps w/EXchan 2
04: 1 Loc :
05: 1 Mult
06: 0 Offset
05: P20 Set Port(s)
01: 9991 C8..C5=nc/nc/nc/high
02: 9999 C4..C1=nc/nc/nc/nc
06: P87 Beginning of Loop
01: 0 Delay
02: 21 Loop Count
07: P86 Do
01: 76 Pulse Port 6
08: P5 AC Half Bridge
01: 1 Rep
02: 14 250 mV fast Range
03: 1 IN Chan
04: 1 Excite all reps w/EXchan 1
05: 250 mV Excitation
06: 6-- Loc :
07: 1 Mult
08: 0 Offset
09: P95 End

10: P20 Set Port(s)
01: 9990 C8..C5=nc/nc/nc/low
02: 9999 C4..C1=nc/nc/nc/nc
11: P59 BR Transform Rf[X/(1-X)]
01: 21 Reps
02: 6 Loc :
03: 1 Multiplier (Rf)
12: P86 Do
01: 10 Set high Flag 0 (output)
13: P77 Real Time
01: 110 Day,Hour-Minute
14: P70 Sample
01: 28 Reps
02: 1 Loc
15: P95 End

Input Location Assignments (with comments):

T:	E:	L:		Key:
1:	4:	1:	Loc :	T=Table Number
1:	8:	6:	Loc :	E=Entry Number
1:	11:	6:	Loc :	L=Location Number
1:	2:	27:	Loc :	
1:	3:	28:	Loc :	

Appendix 2 Soil moisture sensor field evaluation data (on floppy disk).

All field data are listed in ASCII format files on Disk 1.

2.1 Neutron probe data (filename: NPROBE.DAT).
Measurements are for 3 tubes at 6 depths (0.15, 0.25, 0.35, 0.45, 0.55, 0.65).

2.2 TDR data (filename: TDR.DAT).
Measurements for 3 replicates for 4 lengths (15, 30, 45, and 60 cm).

2.3 Tensiometer data (filename: TENS.DAT).
Tensiometer data for 3 sets of tensiometers at 30 and 60 cm depths.

2.4. Watermark logged resistance and temperature data (filename: WM.DAT).
Data for 3 replicated sensors at depths of 15, 30 and 60 cm.

2.5. Gypsum block logged resistance and temperature data (filename: GB.DAT).
Data for 3 replicated sensors for depths of 15, 30, 45 and 60 cm.